1 K-KIDS: A Reconnaissance of the 5000 Nearest K Dwarfs

Our Solar System is comprised of one star, eight planets, and more than a million minor bodies — moons, asteroids, TNOs, and comets. For centuries, astronomers have suspected that some stars are not alone, and have wondered whether or not they are parts of other solar systems like ours. During the past century we have learned that many stars are members of multiple systems, and during the last two decades we have come to understand that many stars do, indeed, harbor planetary systems. Today, astronomers are filling in the details of the stellar and planetary system formation processes, yet a valuable cornerstone for these efforts is yet to be realized — a rigorous reconnaissance of a carefully defined *large* set of the nearest stars for companions.

We propose to explore the nearest ∼5000 K dwarf stars via three surveys to provide fundamental datasets describing their stellar, brown dwarf, and jovian planetary companions. The results will provide a keen understanding of the star and planetary formation processes for these stars and will highlight key targets for systematic terrestrial planet searches. We encompass these surveys into a single comprehensive study called "K-KIDS" that targets stars that are just slightly smaller than our Sun, in a legacy sample that can be explored for decades to come.

Together, Co-PIs Todd Henry at Georgia State University (GSU) and Elliott Horch at Southern Connecticut State University (SCSU) will work with students and colleagues to carry out the scientific program. To set the stage, we began in 2015 with an initial sample of 1048 K dwarfs extracted from *Hipparcos* results and have expanded the sample to 5059 stars using *Gaia* Data Release 2 (DR2). Our ultimate goal is to observe these K dwarfs in the three surveys outlined in Table 1 and Figure 1 (left panel) in a long-term effort. We have initially focused on K dwarfs in an equatorial band (declinations from ±30°), including 1048 stars within 50 pc for the Wide and Speckle Surveys and 304 stars within 25 pc for the Radial Velocity (RV) Survey. We are now pushing to further horizons as resources permit. For the three years of funding requested, we will:

(1) Wide Survey: identify and characterize companions to ∼5000 K dwarfs.

(2) Speckle Survey: expand the high-resolution search from ∼1000 to ∼2500 K dwarfs.

(3) Radial Velocity Survey: expand the RV search from ∼300 to ∼1000 K dwarfs.

(4) Synthesize the results for companion stars, brown dwarfs, and jovian planets orbiting the ∼1000 K dwarfs explored in all three surveys, with a particular focus on the inner 5 AU.

Table 1: *Three Surveys of 5000 K Dwarfs*

Survey	Search	Instrument(s)	Telescopes	This Proposal Effort
Wide	$\geq 1''$	*Gaia*/CCD imaging	SMARTS 0.9m/KPNO 0.9m	∼5000 stars, confirmation
Speckle	$\leq 2''$	'Alopeke/Zorro/DSSI/NESSI	Gemini N+S/DCT/WIYN	∼2500 stars, orbits
Radial Velocity	≤ 5 AU	CHIRON	SMARTS 1.5m	∼1000 stars, orbits and planets

The work proposed here dovetails with our ongoing survey of the nearest M dwarfs in the 25 pc sample (funded separately) that we are currently expanding to ∼5000 stars as well using the *Gaia* DR2 results. Thus, the two surveys together will provide a comprehensive assessment of ∼10000 of the nearest K and M dwarfs, stellar types that together account for 87% of all stars in the solar neighborhood (Henry et al. 2006, 2018).

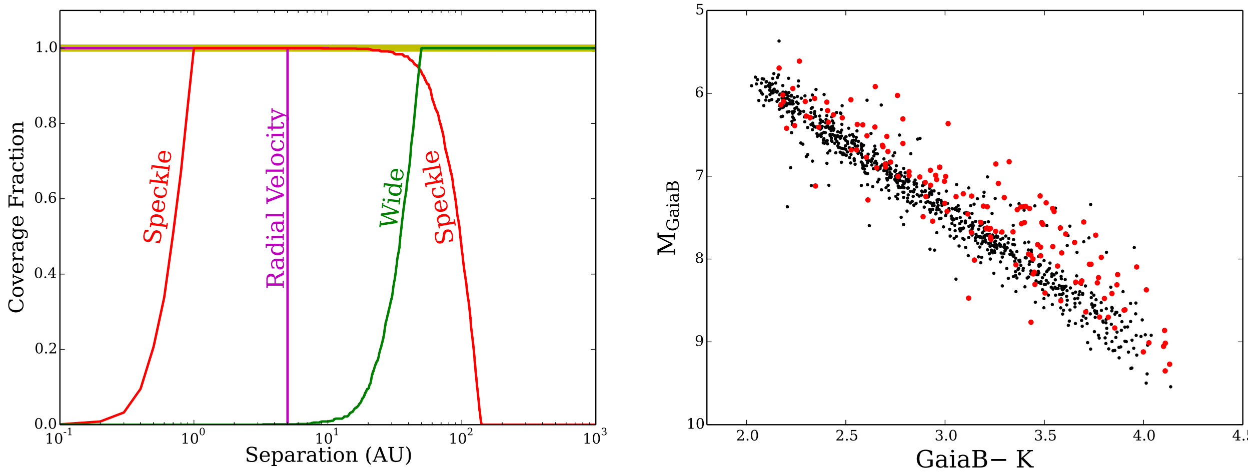

Figure 1: (left) Spatial coverage for the three K-KIDS surveys is shown, with a logarithmic scale on the x-axis and fractional coverage of the sample on the y-axis. Curved edges are shown rather than flat edges for the Wide and Speckle Surveys because the various distances to the K dwarfs have been considered. The Radial Velocity Survey covers 0–5 AU. With all three surveys, there are effectively no coverage gaps 0.1–1000 AU, as outlined with the yellow line. (right) An observational H–R Diagram is shown for the original sample of 1048 K dwarfs. Black points indicate stars observed with speckle imaging that appear to be singles and red points indicate multiples.

2 Three Key Questions

1. Why K Dwarfs?

Multiplicity Studies: Compared to their more massive G-type and less massive M-type counterparts, K dwarfs have been relatively neglected. In fact, in a recent *Annual Reviews* article, Duchene & Kraus (2013) omit an assessment of K dwarf multiplicity altogether, addressing solar-type stars with masses greater than 0.7 $M_\odot$ and red dwarfs less massive than 0.5 $M_\odot$, skipping most of the K dwarfs due to the dearth of survey work. As can be seen by examining the list of stellar multiplcity surveys in Table 2, (ranked by the number of K dwarf systems observed), relatively few K dwarfs have actually been explored.

Exoplanet Searches: The selection of K dwarfs is a major strength of this proposal because they have generally not been systematically surveyed for planets. Most RV and transit programs target either FGK samples in which the bluer, brighter stars dominate the sample, or M dwarfs that permit the smallest planet detections. Furthermore, most surveyors immediately discard obvious binaries, thereby preventing comprehensive assessments of companions.

What is really needed is a careful survey of a volume-limited, effectively volume-complete sample of K dwarfs to discern how often stellar companions, brown dwarfs, and planetary systems form.

2. Why 3 Surveys?

As illustrated in the left panel of Figure 1, three surveys (described in detail in §6) are needed to cover all portions of the phase space of possible companions to the K dwarfs. Stellar companions will be detected in all three surveys, with the Wide Survey reaching to spectral type M8V at 50 pc. The Speckle Survey reaches magnitude differences of $\sim$4 mag in the 8800Å filter at separations of $0.''01$–$0.''1$ and $\sim$5 mag from $0.''$–$2.''0$, corresponding to spectral types M3V and M5V, respectively, at 50 pc for the intrinsically brightest K dwarfs. With a goal of surveying 0–5 AU, the Radial Velocity Survey reaches past the end of the stellar main sequence and through the brown dwarf regime easily, and will detect planets of jovian masses as well — thus, it is key to understanding the differences in formation rates and orbital characteristics of all three types of objects.

Table 2: *Surveys of K Dwarfs*

Reference	Spectral Types	# Total Systems	# K Systems	Search Region	Technique	Notes
Bonfils et al. (2013)	M	102	0	P < 6 yrs	radial velocities	11 pc
Duquennoy & Mayor (1991)	FG	164	0	P < 13 yrs	radial velocities	
Reiners et al. (2018)	M	324	0	recent start	radial velocities	CARMENES
Winters et al. (2019)	M	1120	0	0–1000 AU	various	25 pc, **SUBMITTED**
Tokovinin et al. (2014)	FG	4847	0	0–1000+ AU	various	67 pc
Ward-Duong et al. (2015)	KM	245	11	3–10000 AU	adaptive optics	15 pc
Valenti et al. (2005)	FGK	1040	66	none	radial velocities	not companion survey
Gaidos et al. (2013)	K	110	85	P < 4 yrs	radial velocities	
Horch et al. (2012)	AFGK	384	99	0.05–2″	speckle imaging	multiples only
Horch et al. (2011a)	AFGK	497	118	0.05–2″	speckle imaging	
Raghavan et al. (2010)	FGK	454	165	0–1000 AU	various	25 pc
Tokovinin et al. (1992)	KM	200	167	P < 3000 days	radial velocities	
Halbwachs et al. (2018)	GK	269	261	P < 13 yrs	radial velocities	preprint
Paredes et al. (2019)	K	304	304	0–5 AU	radial velocities	25 pc, **K-KIDS**
Nusdeo et al. (2019)	K	1048	1048	0.01–2″	speckle imaging	50 pc, **K-KIDS**
Proposed Here	K	5059	5059	0–1000 AU	various	50 pc, **K-KIDS**

3. Why 5000 stars?

Our goals in understanding the star/planet formation process go beyond simply determining the fraction of all K dwarfs with various types of companions. We wish to determine multiplicity rates through four decades of separations, from 0.1–1000 AU, and in particular need to increase the number of companions in the comparatively rarified outer two decades. We are interested not only in the overall statistics of stellar, brown dwarfs, and jovian planets to K dwarfs — we wish to tease apart the effects of primary mass, metallicity, and age as well, and to explore the overall hierarchical structures of K dwarf systems.

For each of these characteristics, large numbers of stars need to be observed in order to have significant numbers in various subsamples. Dividing 5000 K dwarfs into four groups boosts each group to 1250 stars, enabling clear disentanglement of any trends that are seen. We are particularly interested in bolstering the subsamples of young stars above and subdwarfs below the main sequence (Figure 1, right panel) to evaluate trends in metallicity and age, both of which will be determined using the RV spectra (see §6). For example, in the volume-limited 25 pc set of 552 M dwarfs in the southern sky examined by Silverstein (2017 and continuing Ph.D. work), there are 50 stars (9.1%) estimated to be younger than 100 Myr and only 28 stars (5.1%) classified as subdwarfs. Making the reasonable assumption that K and M dwarfs have similar fractions of young and old stars in the solar neighborhood, we anticipate that there will be ∼460 young K dwarfs and ∼260 old K dwarfs in our sample of 5059 stars. Thus, because the fractions of young and old stars are rather low, we need a very large sample to yield statistics on even the most basic information on stellar mulitiplicity for stellar populations of various ages. Similar arguments can be made for slices in primary masses, temperatures, metallicity, etc.

3 Intellectual Merit: Reach of the K Dwarf Survey

The ambitious survey proposed here provides a bridge between stellar and planetary formation work by exploring a large sample of K dwarfs for many types of companions at various separations. K dwarfs have been selected because there are sufficient numbers of them nearby to provide a large sample searchable throughout a wide range of separation regimes, and are bright enough to be observed with many telescope/instrument combinations. In addition, K dwarfs are very much, if not exactly, like our Sun, thereby providing context for the history of our Solar System.

Previous searches for companions to nearby stars similar to the Sun have typically included hundreds of stars, rather than the ∼5000 proposed here (Table 2). In their pioneering work, Duquennoy and Mayor (1991) found that roughly half of 164 F and G stars in a volume-limited survey were multiples. Subsequent updates (Udry et al. 1998, Raghavan et al. 2010) have built upon these results, and reached similar conclusions. The largest survey of solar-type stars to date includes 4847 F and G stars (Tokovinin 2014), in which ∼80% of stellar companions have been detected, but in which only ∼30% of tertiaries and additional companions have been identified. However, these studies have not *systematically* sampled *all* separation regimes, relying instead on programs reporting companions found during various heterogeneous imaging and RV efforts that did not search all stars in the samples.

At lower masses, the most comprehensive studies are those of Ward-Duong (2015), who surveyed 245 K and M dwarfs within 15 pc from 3–1000 AU using adaptive optics and wide-field searches, and that of Winters (2019, submitted), who searched 1120 M dwarfs within 25 pc, at regions from 2″ outward, with additions for closer systems as available. Both studies found a multiplicity rate of ∼25%. A radial velocity survey of 1000+ M dwarfs is currently beyond most programs (see, e.g., Bonfils et al. 2013, who observed 102 M dwarfs), although CARMENES is targeting 324 M dwarfs (Reiners et al. 2018) and Winters is currently observing a similar number within 15 pc.

Two things complicate results from most of these surveys: (1) some stars are omitted from observing lists entirely, e.g., binaries from RV surveys, and (2) null detections are often not reported, resulting in the need for various, sometimes uncertain, correction factors. In a comprehensive assessment of RV surveys, Grether & Lineweaver (2006) showed that among stars within 25 pc selected using *Hipparcos* results, ∼90% of K0V stars, 50% of K5V stars, and only 10% of K9V stars were being targeted for planets. They sum up the problem well, even for Sun-like stars: "Doppler survey target selection criteria often exclude close binaries (separation <2″) from the target lists and are not focused on detecting stellar companions. Some stars have also been left off the target lists because of high stellar chromospheric activity." We will address these problems by observing *all* stars in the sample.

The cartography resulting from our K-KIDS survey will provide the most comprehensive assessment of companions orbiting a large number of stars ever attempted. A key goal is to map the phase space of companion mass vs. separation to tease apart the formation outcomes for objects from 0–5 AU spanning the range from 1 Jupiter mass to 80% the mass of the Sun. We will also learn which stars orbit one another in such configurations that make it difficult for the creation of planets, and create a vetted list of the nearest K dwarfs with *no* known companions. These stars will become high priority targets for more sensitive searches for lower mass, potentially habitable planets, as new technology allows us to peer ever deeper for worlds like our own.

Using the large sample of ∼5000 stars, our goals are to address the following questions:

1. What is the stellar companion population at separations of 0.1–1000 AU around a large, carefully vetted set of K dwarfs? How does this compare to the multiplicity rates of ∼50% for G dwarfs and ∼25% for M dwarfs?

2. What is the rate of hierarchical systems for K dwarfs, and how often are stars *and* brown dwarfs/jovian planets found in the same system?

3. What is the mass distribution of companions orbiting K dwarfs?

4. Are there detectable trends in multiplicity with metallicity and age for K dwarfs?

5. How do the stellar, brown dwarf, and jovian planet populations compare — e.g., orbital semimajor axes and eccentricities — on Solar System scales for K dwarfs, and what does this tell us about star, brown dwarf, and exoplanet formation processes?

4 Results from Prior NSF Funding

Previous NSF funding to Co-PIs Henry (GSU) and Horch (SCSU) has come in three forms, in combination and individually, each of which is detailed here.

Henry and Horch secured funding together to work on speckle imaging of nearby stars through NSF grants AST-1517413/1517824 (*Collaborative Research: Exploring the Nearest Stars on Solar System Scales*, 10/01/2015 to 09/30/2018, $243K to GSU, $335K to SCSU). During the past three years, the K-KIDS project has matured, building to a team that includes Henry and graduate students Leonardo Paredes, Dan Nusdeo (previously at SCSU), and Hodari James at GSU. At SCSU, Horch, research scientist Dana Casetti, graduate students Sam Weiss, Nicole Granucci, and Hannah Hocutt, and undergraduates Nicole Hess and Hana Girum have worked on the K-KIDS project. During the three years, K-KIDS activities include:

• The initial sample of 1048 K dwarfs has been defined and vetted. An additional 4011 K dwarfs have been extracted from *Gaia* DR2 and evaluation has commenced. Results of sample construction and evaluation were presented via two AAS posters (Paredes et al. 2017, 2018).

• Overviews of the K-KIDS project were given in invited talks by Henry at the Division on Dynamical Astronomy AAS Meeting (June 2017 in London, UK) and at the Know Thy Star Conference (October 2017 in Pasadena, CA).

• All 1048 K dwarfs have been observed in the Speckle Survey. Reductions were completed by Horch's team at SCSU in October 2018. First results were presented via two AAS posters (Nusdeo et al. 2017, 2018), and updated results are shown in Figures 1 and 2.

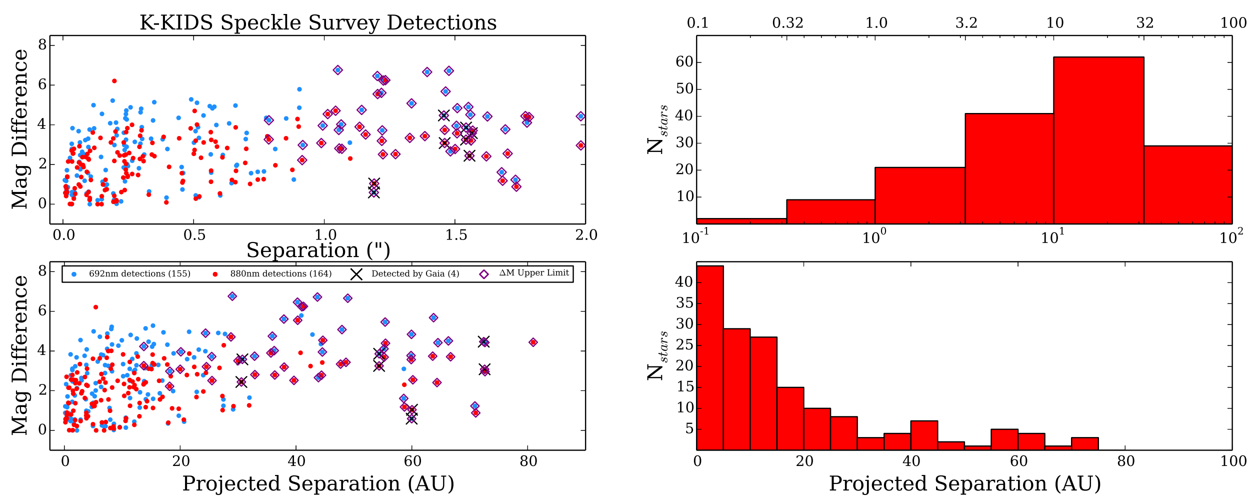

Figure 2: Results from the Speckle Survey to date are shown. (left) Magnitude differences for multiples measured with DSSI in the 692nm (blue points) and 880nm (red points) filters. The upper panel shows observed separations on the sky and the lower panel shows projected separations in AU. Pairs of measurements are displaced vertically at different magnitude differences in the two filters for each pair at a given epoch. Diamonds represent upper limits at large separations because of decorrelation between the primary and secondary speckle patterns when separations approach the size of the isoplanatic patch (Horch et al. 2011b). Only 4 of the 164 companions were detected by *Gaia*, shown with pairs of black Xs. (right) The distribution of DSSI-detected companions is shown in projected separation in AU in both log space (upper) and linear space (lower).

• The 1048 K dwarfs have also been searched in the Wide Survey, including *Gaia* DR2 detections. Early results of the combined Wide and Speckle Surveys were presented by Nusdeo at the Know Thy Star Conference (October 2017 in Pasadena, CA). A nearly complete paper presenting all imaged companions is drafted and is to be submitted to *AJ* by the end of 2018 (Nusdeo et al. 2019).

• Paredes and Henry reopened the CTIO/SMARTS 1.5m in June 2017 to test the feasibility of the CHIRON spectrograph for the K-KIDS RV survey. We now lead operations of the 1.5m, with new SMARTS observer Rodrigo Hinojosa observing every other week, and have observed 270 K dwarfs as of November 2018.

• The Keck/HIRES and ESO/HARPS archives have been checked for observations of the 1048 K dwarfs already made by other RV teams. As of July 2018, 794 K dwarfs have fewer than 10 observations, of which 528 have zero observations.

• A systematic canvassing of all K dwarfs within 50 pc for known young stars and known exoplanets has been initiated as part of graduate student Hodari James' Ph.D. work.

• Paredes presented early results from the Radial Velocity Survey at the Know Thy Star Conference (October 2017 in Pasadena, CA); updated results are shown in Figures 3 and 4. A paper presenting RV results for stars within 25 pc is drafted and is to be submitted to *AJ* in the spring of 2019 (Paredes et al. 2019).

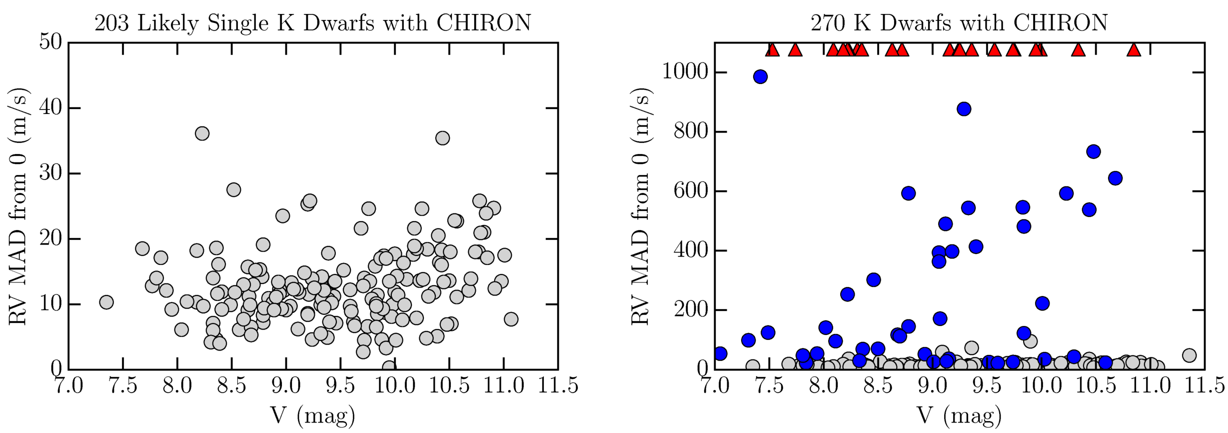

Figure 3: (left) Results from the Radial Velocity Survey are shown for 203 K dwarfs that appear to be single stars observed on weekly, monthly, and yearly timescales. All stars have velocity residuals from a flat line less than 40 m/s, measured as Mean Absolute Devations (MAD values). The best stars have MADs of 5 m/s or less, and there is a slight trend upward to 25 m/s for the faintest K-KIDS observed. (right) The full sample of 270 stars with velocities to date is shown. Blue points indicate perturbations with amplitudes up to 1000 m/s and red points are for stars with amplitudes in excess of 1000 m/s.

• Horch gave invited talks at both the SPIE Astronomical Telescopes and Instrumentation meeting in Edinburgh, Scotland and the Dynamical Astronomy in Latin America VII conference in Bogotá, Colombia in 2016, in which he discussed the GSU/SCSU binary star efforts.

• The SCSU team led the reduction and analysis of a large collection of speckle observations taken at WIYN. In addition to reporting over 2500 speckle measures of binary stars, the work produced first orbit determinations for three stars on the K-KIDS list (Horch et al. 2017).

• Horch worked closely with Mark Everett, NESSI instrument scientist at WIYN, to write the data reduction code for NESSI. NESSI can now be used for K-KIDS follow-up and data can be rapidly reduced for all users.

• A new remote observing room has been set up at SCSU and used in observations taken at WIYN, DCT, and most recently, both Gemini telescopes. Several students have helped with the observations, giving them their first experiences observing with large telescopes.

Henry has had long-term funding as Director of the REsearch Consortium On Nearby Stars, (RECONS, *www.recons.org*) through NSF grants AST-0507711/0908402/1412026/1715551. RECONS was formed in 1994 to explore the solar neighborhood, and ultimately to understand the objects that make up our Galaxy, both individually and as a population (Henry et al. 2006). RECONS carries out fundamental research to discover "missing" members of the sample of stars within 25 parsecs and to characterize all stellar systems within that distance limit. New members are found via astrometric, photometric, and spectroscopic techniques, or through companionship studies at small and large separations. Characterization includes photometry and spectroscopy at both optical and infrared wavelengths, as well as determinations of the luminosity function, mass function, and multiplicity fraction of the nearby stars.

RECONS results have primarily been published in a series of 44 papers in *The Solar Neighborhood* series in *The Astronomical Journal*, (a library of the papers is provided at *www.recons.org*). The 29 most recent papers were supported by NSF, making important contributions to stellar population studies of red/brown dwarfs, cool subdwarfs, white dwarfs, and young stars. The cornerstone of the RECONS effort is an astrometry/photometry program underway since 1999 at the CTIO 0.9m, which Henry operates for the SMARTS Consortium that he helped found in 2003. With its 2K×2K CCD camera, the 0.9m has proven to be a powerful astrometric/photometric facility, and the discovery of hundreds of new nearby stars via trigonometric parallax work has allowed RECONS to create the world's best list of the nearest stars (Henry et al. 2018).

Horch has had funding from NSF to build the DSSI speckle camera (AST-0504010/0751361), which led to several speckle campaigns, such as observing *Hipparcos* and other key binaries at WIYN to understand the effects of metallicity and age on the Mass-Luminosity Relation (AST-0908125). Since the 2013 completion of the WIYN project, DSSI has been used at both Gemini telescopes and DCT in K-KIDS work and in follow-up observations for NASA's *Kepler/K2* mission. Horch has used DSSI with Steve Howell (NASA Ames) and Gerard van Belle (Lowell Observatory) to make *Kepler/K2* related observations, yielding dozens of exoplanet-related papers, including Horch et al. (2014), Everett et al. (2015), Crossfield et al. (2016), Howell et al. (2016), Hirsch et al. (2017), and Furlan et al. (2017). DSSI now spends much of its time at DCT, where it is being used in a collaborative research grant of Horch and van Belle to survey nearby, recently discovered M dwarfs for companions (AST-1616698, target list provided by Winters and Henry). Approximately 1000 diffraction-limited observations have been taken at DCT on this project since 2016.

Horch's other work funded by NSF involves instrumentation development of a wireless optical intensity interferometer (AST-1429015). The Southern Connecticut Stellar Interferometer (SCSI) was completed in 2016 and is now used to make photon correlation measurements with two 0.6m Dobsonian telescopes outfitted with SPAD detectors on the SCSU campus (Horch et al. 2016). Such measurements provide stellar diameters at visible wavelengths with a relatively inexpensive set-up. The SCSI prototype has already made important technology demonstrations, producing several nights of high-quality photon-correlation data currently under analysis. With GPS timing at each telescope, we expect wireless operations with SCSI to begin by late 2019, which will allow for baselines much larger than the 2–4m that have been used so far for engineering purposes, perhaps larger than the baselines of existing Michelson-style interferometers. The science that can be enabled by this project includes resolving the motions of spectroscopic binaries over many orbits to make ultra-precise tests of stellar evolution. Intensity interferometry at blue wavelengths also promises breakthroughs in the measurements of stellar disks and limb darkening.

5 Sample of 5000 K Dwarfs

Among the 378 stars known within 10 pc of the Sun, there are 44 K dwarfs, representing 12% of the stellar population (Henry et al. 2006, yearly updates at *www.recons.org*). This makes K dwarfs the second most populous type of star in the Galaxy, after the M dwarfs that account for 75%, and more than twice the 5% fraction of G dwarfs. Nearby K dwarfs fall in a "sweet spot" of target accessibility, as large numbers of them are bright enough for both high-resolution imaging and RV surveys. K dwarfs have the added benefit that they are among the photometrically quietest of all stars, with minimal RV jitter due to chromospheric activity (Isaacson & Fischer 2010). Thus, K dwarfs provide an ideal opportunity for a large-scale effort to understand the formation processes of companions of various types through a wide range of separations.

To avoid the pitfalls of input sample bias, we target an all-sky, volume-limited, and effectively volume-complete sample of K dwarfs. The sample is outlined in Table 3 — three equatorial subsamples include K dwarfs found between declinations +30 and −30, so that each star can be observed from all major observatories on Earth (mimicking the idea behind Landolt's equatorial photometric standards), and the complete sample is all-sky. The star counts contributed by *Hipparcos* and *Gaia* are given, yielding totals of 304, 720, and 2555 K dwarfs in the equatorial samples at horizons of 25 pc, 33 pc, and 50 pc, and 5059 in the all-sky 50 pc sample. Our original equatorial 50 pc sample of 1048 stars from *Hipparcos* is listed, and noted in the "Wide Done" and "Speckle Done" columns as being already completely observed. Further details about the RV samples are given in §6.

Table 3: *K-KIDS Sample*

Sample	Source	# Stars	Wide Done	Speckle Done	RV Other Done	RV Us Done	RV All Done
25 Parsec Equatorial	*Hipparcos*	217	217	217	113	104	217
25 Parsec Equatorial	*Gaia* adds	77	0	0	0	20	20
25 Parsec Equatorial	TOTALS	304	217	217	113	124	237
33 Parsec Equatorial	*Hipparcos*	472	472	472	172	250	422
33 Parsec Equatorial	*Gaia* adds	248	0	0	0	20	20
33 Parsec Equatorial	TOTALS	720	472	472	172	270	442
50 Parsec Equatorial	*Hipparcos*	1048	1048	1048	254	250	504
50 Parsec Equatorial	*Gaia* adds	1507	0	0	0	20	20
50 Parsec Equatorial	TOTALS	2555	1048	1048	254	270	524
50 Parsec All-Sky	3 YEAR GOALS	5059	5059	2555	—	1000	1254

The sample is described by the following criteria:

1. Volume-limited — all stars have $\pi_{trig} \geq 20$ mas, placing them within 50 pc. Most stars come from *Gaia* DR2, but the brightest are from *Hipparcos* results because they are saturated in *Gaia*. Additional stars missing astrometric solutions in *Gaia* and *Hipparcos* are also included.

2. Volume-complete — *every* star that meets the sample criteria will be targeted in the surveys. For example, binaries separated by $\leq 2''$ will not be dropped from the Radial Velocity Survey. A careful check of the overall target distribution shows the expected $\leq$5% variations in numbers in equal volume shells all the way to 50 pc. This is expected given that the faintest K dwarfs have $GaiaB \sim 12$ while *Gaia* reaches to $GaiaB > 20$. The only notable offset is a ∼10% *overdensity* from 45–48 pc due to the Hyades Cluster; these stars will be included in the surveys.

3. K Dwarf Luminosities and Colors — "K dwarfs" have been defined by comparison to key spectral typing schemes, most notably that of Gray et al. (2003, 2006), who looked at 2340 stars within 40 pc earlier than type M0. We adopt the ranges of M_{GaiaB} = 5.30–9.90 and $GaiaB - K$ = 2.00–4.00 or M_V = 5.80–8.80 and $V - K$ = 1.90–3.70 that correspond to spectral type K. To ensure that we do not miss any stars that might eventually meet these criteria due to updated photometric measurements, we extend each limit slightly, by 0.05 mag in color and 0.10 mag in absolute magnitude at both the blue and red ends. *A key aspect of the K-KIDS sample is that 93% of the K dwarfs have GaiaB = 8–12, with the remaining 7% brighter than GaiaB = 8. Thus, all K dwarfs can be observed efficiently in the three surveys.*

When we began K-KIDS in 2015, *Gaia* results were not available. We therefore extracted a sample of 1048 K dwarfs in the equatorial region within 50 pc using *Hipparcos* results (van Leeuwen 2007), V magnitudes converted from Tycho V_T (Perryman et al. 1997, Bessell 2000), and

K_s magnitudes from 2MASS (Skrutskie et al. 2006). This sample is shown in the observational H–R Diagram in Figure 1, updated with *Gaia* parallaxes. Stars not known to have any stellar companions are shown in black, whereas those with companions detected in the Speckle Survey are shown in red. As expected, many of the elevated points have close companions detected with speckle imaging because unresolved binaries are elevated in luminosity due to excess flux. One tantalizing early result is that when slicing the sample into three equal groups of 349 stars each in color space, we find 35 companions for K dwarfs with $GaiaB - K$ = 2.00–2.65, 54 for 2.66–3.24, and 75 for 3.25–4.14 (Nusdeo et al. 2019). Thus, at least for stellar companions in the speckle regime, the multiplicity rate *climbs* for redder colors and lower masses. This is in contrast to the trend of decreasing multiplicity rates from G dwarfs (∼50%) to M dwarfs (∼25%) described above.

Using the *Gaia* DR2 results released in April 2018, we have now extracted a sample of 5059 K dwarfs within 50 pc covering the entire sky. As outlined in §1 and noted in the final line of Table 3, our three year goals are to complete the Wide Survey for all 5059 stars (all-sky sample to 50 pc), expand the Speckle Survey to 2555 stars (equatorial sample to 50 pc), and expand the Radial Velocity Survey to 1000 stars (equatorial sample to a bit beyond 33 pc). The Radial Velocity Survey is the most time-consuming (see §6), so we are currently focusing on the equatorial 33 pc sample and will push further as time permits. This is a prudent plan given the statistics of companion demographics — at larger separations, fewer companions are found, so larger numbers of stars need to be surveyed for statistically robust results. Our ultimate goal *is* to survey all 5059 stars in all three surveys ... but, one step at a time.

6 Research Plan: Three Surveys of K Dwarfs

Here we outline the research plan during the proposal period for each of the three surveys. The GSU and SCSU teams will work together to combine RV and imaging data and to present results. In order to carry out this very large survey, specific tasks are divided as follows:

GSU Team (1) create and vet the sample, (2) coordinate RV observations, (3) reduce/analyze RV data, (4) derive metallicities and ages from spectra, (5) combine RV and imaging data for companion statistics from 0.1–1000 AU, and (6) analyze orbital statistics.

SCSU Team (1) coordinate speckle observations, (2) reduce/analyze speckle data, (3) derive astrometric positions and component fluxes, (4) fold masses into mass-luminosity relations.

Access to the necessary telescope/instrument combinations for the work proposed here is described in detail in the Facilities addendum. Briefly, as the Principal Scientist of the SMARTS (Small and Moderate Aperture Telescope System) Consortium, Co-PI Henry oversees the 1.5m, 1.3m, 1.0m, and 0.9m telescopes at CTIO. In particular, Henry is the Operations Manager for the the two telescopes used for this work — the 1.5m and 0.9m — providing guaranteed access and control of scheduling to accomplish the survey goals. In addition, both Henry and Horch are members of the Speckle Team (including Mark Everett at NOAO, Steve Howell at NASA Ames, and Gerard van Belle at Lowell Observatory, among others) that organizes the queues and makes the observations for the four speckle cameras on the Gemini, DCT, and WIYN telescopes.

Wide Survey (led by graduate student Dan Nusdeo)

The first step in finding wide companions to the K dwarfs is to trawl the *Gaia* DR2 results, which have made this search relatively straightforward. We have found that by matching parallaxes to 1 mas and proper motions to 40 mas/yr, true companions are recovered. We have recovered nine real objects in *Gaia* DR2 with $GaiaB$ = 21.0–21.5, one with $GaiaB$ = 21.7 (2MASS 2148+4003) and one with $GaiaB = 22.2$ (SDSS 1416+1348AB).[1] We adopt a conservative limit of $GaiaB = 21.5$ for companions to K dwarfs. For the coolest red dwarfs, $GaiaB = 21.5$ corresponds to $V = 21.2$ (Jao et al. 2018), which matches the luminosities of the smallest stars at spectral type L2V (Dieterich et al. 2014). Thus, at 10 pc where $M_V = 21.2$, we can detect companions to the end of the stellar main sequence in *Gaia* DR2. Even at the 50 pc horizon of the survey, we reach $M_V = 17.7$, which corresponds to M8V. So, nearly all of the stellar companions can be found in *Gaia* DR2 all the way to 50 pc. There remain cases when the detections are ambiguous, such as in crowded fields or at separations less than a $\sim 2''$. Tried-and-true blinking of SuperCOSMOS frames, in which RECONS members are well-versed (e.g., Boyd et al. 2011), usually confirms or refutes a candidate companion because background sources are evident in plate images from decades ago.

We use the optical $GaiaB$ and $GaiaR$ magnitudes, near-infrared JHK photometry from 2MASS, and infrared photometry from $WISE$ to create spectra energy distributions for each companion. The broad stretch of photometry allows us to verify the nature of the companion, e.g., a red or white dwarf. For the $\sim$2% of sources in *Gaia* DR2 that do not have colors, and objects that need to be vetted, we take VRI images at the CTIO/SMARTS 0.9m to confirm/refute companions and to fill in the optical photometry. We reach to $VRI = 21$ at the 0.9m, with errors typically 0.03 mag (Winters et al. 2011), effectively reaching all stellar companions out to 50 pc, at least in the I filter. We have also used the KPNO 0.9m and Lowell 42in for northern hemisphere targets in the past, and a few short observing runs would suffice to acquire any needed photometry. To date, we have found 165 companions to the 1048 K dwarfs in the Wide Survey, for a multiplicity rate of 16% at large separations. We are currently collecting photometry from other databases and the 0.9m to enable final assessments of the companions, but the Wide Survey for the original 1048 K-KIDS is effectively done. **Because the search methodology and required follow-up are relatively straightforward, we propose to search all 5059 stars in the all-sky 50 pc K-KIDS sample in the three year period of the proposed work.**

Speckle Survey (led by graduate student Dan Nusdeo)

As described in the Facilities addendum, four speckle cameras are available to make observations on the Gemini-North 8.1m ('Alopeke), Gemini-South 8.1m (Zorro), DCT 4.3m (DSSI), and WIYN 3.5m (NESSI) telescopes. The original camera, the Differential Speckle Survey Instrument (DSSI), was built by Co-PI Horch at SCSU. In addition to making precise astrometric measurements, DSSI's great advantage over most speckle cameras is that it collects simultaneous images of two speckle clouds in different filters by using a dichroic beamsplitter that places the images on two electron-multiplying CCDs. There are three advantages of this dual-imaging approach: (1) twice as many speckle frames are collected in a single observation, making observations more efficient, (2) colors of components are determined in a single observation, and (3) the two datasets give the ability to distinguish between residual atmospheric dispersion and duplicity in the case of elongated speckles. This permits the detection and characterization of binary stars with separations as small as one-quarter of the telescope diffraction limit (Horch et al. 2011b): $\sim$5 mas at Gemini and $\sim$10 mas at DCT. DSSI therefore reveals companions at smaller separations than adaptive optics or traditional speckle imaging systems, allowing us to image companions to K dwarfs as close as 0.25 AU, well inside the orbit of Mercury, even at the 50 pc horizon of the survey.

All 1048 K dwarfs in the initial sample have been observed with DSSI, most at Gemini-North and South where DSSI provides a field $2''.8$ on a side. A few hundred of the nearest K dwarfs have been observed at WIYN, where the field is $5''.6$ on a side, but because of their proximity the same regions around the stars are covered. A typical DSSI observation set includes 1000 images 40–60

[1] Neither of the two faintest objects are companions to K dwarfs, but are selected for illustrative purposes.

msec in duration on each star, and ∼100 stars are typically observed per clear night. The limiting magnitudes for diffraction-limited imaging are $V = 17$ at Gemini, $V = 15$ at DCT, and $V = 14$ at WIYN, all limits that are much fainter than our sample K dwarfs with $V \leq 12$.

Results of the Speckle Survey on the 1048 K dwarfs in the equatorial 50 pc sample are shown in Figures 1 and 2 and will soon be submitted to *AJ* (Nusdeo et al. 2019). To date, we have found 164 candidate companions in the Speckle Survey — nearly the same as the 165 in the Wide Survey, with only a few companions in common. Primaries with speckle-detected companions are shown with red points in Figure 1. A handful of these systems are already known to be hierarchical, so the multiplicity rate from the Speckle Survey alone is 15%. Second epoch observations are underway to confirm or refute companions quickly, possible because effectively all of the K dwarfs within 50 pc have proper motions large enough to disentangle true companions from background sources in one year. The left panel of Figure 2 illustrates the magnitude differences for the companions, plotted at both observed spatial separations in the top (in arcseconds) and projected physical separations in the bottom (in AU). Narrow band filters are used, typically 6920Å (blue points in the left panel of Figure 2) and 8800Å (red points), to maintain speckle coherence. Companions ∼4 mag fainter than the primaries can be detected at separations of 0.″01–0.″1 and ∼5 mag from 0.″1–2.″0, corresponding to companions with spectral types M3V and M5V, respectively, even at 50 pc for the intrinsically brightest K dwarfs. Ironically, measurements at *larger* separations are often assigned upper limits, because of decorrelation between the primary and secondary speckle patterns when separations approach the size of the isoplanatic patch (Horch et al. 2011b). All of these companions have been searched for in *Gaia* DR2 and only 4 of the 164 were found, and only at separations larger than 1.″0 (pairs of Xs in Figure 2). *Thus, speckle imaging reveals many companions to which Gaia is insensitive.* The right panel of Figure 2 shows the projected spatial separations of the companions in both log (top) and linear (bottom) space. What is already clear is that there are *many* stellar companions to K dwarfs on the scale of our Solar System from 0.32–32 AU. It is also evident that there is a long tail in the distribution of companions beyond 30 AU, and that a larger sample is needed to map the character of this distribution.

During the three years of proposed work, we will expand the Speckle Survey sample from the original 1048 *Hipparcos* stars to the 2555 stars in the effectively complete *Gaia* equatorial 50 pc sample. This will be possible because there will be four speckle cameras available to use and all stars can be observed from both hemispheres. One of the most exciting aspects of continued Speckle Survey is the overlap in detections with the RV survey discussed next. With speckle resolution and colors, RV orbits, and *Gaia* parallaxes, we have a goal to determine the masses of at least 100 K dwarfs and their companions to better than 1%. We can then map the masses to luminosities, temperatures, metallicities, and ages from the combined data, and explore how the multiplicity of K dwarfs changes as a function of all of these parameters.

Radial Velocity Survey (led by graduate students Leonardo Paredes and Hodari James)

The RV program is an ambitious effort to (eventually) survey at least the 2555 K dwarfs in the 50 pc equatorial sample using the CTIO/SMARTS 1.5m and CHIRON spectrograph. The 1.5m has been operated by SMARTS since 2003, but was temporarily closed in June 2016. Co-PI Henry and graduate student Paredes reopened the telescope in June 2017, and this program is the core effort at the 1.5m — by supporting this work, the 1.5m can remain open for users worldwide and 1.5m SMARTS Fellow Paredes has a stable position for the duration of his Ph.D. work. Henry has secured $50K/year of support from GSU (250 hours at $200/hour) and we earn 10% additional time per year for running telescope operations (240 hours). We observe 3 K-KIDS/hour with 900 second integrations and overheads. Assuming 15% losses for weather and telescope issues, we can make 1250 RV observations/year or 3750 observations during the three years of the proposed work.

Our initial focus was to complete the 25 pc equatorial sample from *Hipparcos*, and those 217 stars have now been "observed" by our program (104 stars) or by others (113 stars). A star is considered "observed" when we (or others) have acquired 2–3 spectra on each of three timescales — weekly, monthly, and yearly. If no perturbation is seen with all three cadences in-hand, the star is retired from the observing list. If a perturbation is seen, observations continue at intervals appropriate to the velocity variations, e.g., nightly if changes are seen in a week and monthly if seen over a year. We have carefully checked for stars already sufficiently observed in the Keck/HIRES and ESO/HARPS RV programs, as well as those with orbits in the *Ninth Catalog of Orbital Elements of Spectroscopic Binary Stars* (Pourbaix et al. 2004 with continuing updates at http://sb9.astro.ulb.ac.be), in the NASA Exoplanet Archive, and via literature and SIMBAD searches. Results of these searches for K-KIDS are reflected in the "RV Other Done" column of Table 3.

Our initial results from the 25 pc sample (parallax cutoff 40 mas) are surprising: among the 104 stars we have observed, 38 exhibit perturbations, of which only 12 were previously reported. The numbers grow quickly past 25 pc — among the 270 stars we have observed within 33 pc, there are 67 with perturbations, only 17 of which were previously known. Clearly, there are many discoveries remaining to be made, even among the very closest K dwarfs. We have already begun pushing to 33 pc (parallax cutoff 30 mas) and include the new *Gaia* additions, for a total of 720 stars, of which 442 can now be considered observed (270 by us and 172 by others).[2]

The CHIRON high-resolution optical spectrograph was built specifically to carry out radial velocity surveys, although many other types of observing programs are underway. CHIRON was designed for high throughput and stability and provides a fixed spectral range of 4150–8800Å (Tokovinin et al. 2013). Wavelength calibrations are done using a ThAr lamp or iodine cell. We use CHIRON in "slicer mode" that provides R = 79000 spectra, and calibrate the wavelength scale using the ThAr lamp. The Radial Velocity Survey is led by graduate student Leonardo Paredes, who built the cross-correlation pipeline that uses 25 of the 59 CHIRON orders to determine RVs. Results are summarized in Figure 3. The left panel shows that we routinely obtain RV precisions of 5–25 m/s for presumably single K dwarfs with V = 7.5–11.0, with a slight degradation in precision for fainter stars. The right panel shows the clear delineation between the 203 stars we consider to be singles (gray points) and the 67 with perturbations (blue and red points). Our multiplicity rate of 25% for the 270 stars is roughly twice that of Halbwachs et al. (2018), who provided orbits for 34 of 261 K dwarfs (13%). Careful vetting and follow-up of the perturbations in our survey should bring the picture of the companion population into clear focus.

Figure 4 illustrates results for 10 stars in the survey to date, including a reference "flatline" star, three stars with newly discovered stellar companions with orbital fits, two stars with long-term trends caused by stellar or brown dwarf secondaries, and two exoplanet candidates. The lower left panel illustrates our data for a known exoplanet with miniumum mass 1.1 M_{Jup} in an 11-day orbit, and the lower right panel shows our new discovery of a transiting exoplanet orbiting the K dwarf HIP 65 with mass 2.9 M_{Jup} in a 1-day period detected by *TESS* (Paredes et al. 2018, to be submitted). Gaidos et al. (2013) have arguably done the most thorough job so far in understanding the jovian planet fraction of K dwarfs, finding that 4.0±2.3% of 110 stars have gas giants with orbital periods $<$ 245 days. For the 1000 stars we will survey during the grant period, this implies that we will find between zero and a hundred jovian planets. **By the end of the proposal period, our goal is to survey 1000 K dwarfs within ∼35 pc. We will then reach the 5-year observation mark of CHIRON observations, which will allow us to determine the jovian planet rate, and to compare the populations of hot Jupiters (0–1 AU) to warm Jupiters (1–3 AU) ... and begin to explore the realm of cold Jupiters (> 3 AU).**

[2]Because the *Gaia* additions were not in *Hipparcos*, they were not observed in other RV surveys.

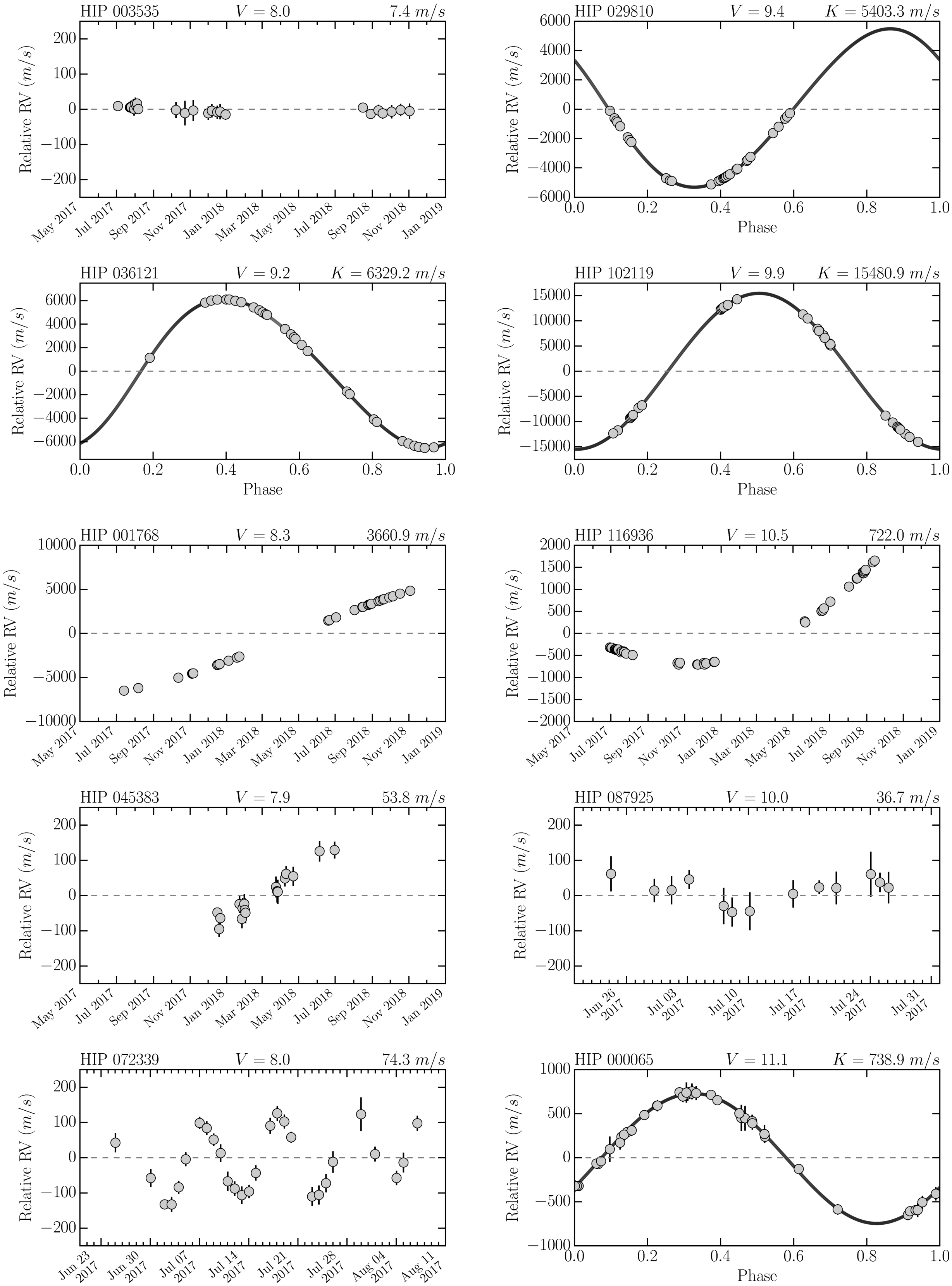

Figure 4: Results for 10 K-KIDS observed during the RV program are shown, including star names, V mags, and Mean Absolute Deviations (MADs) from zero velocity, except for the four cases with orbital fits, which show velocity semiamplitudes, K. The top left panel illustrates results for a single star, indicative of CHIRON's ∼10 m/s precision. The top right panel and second row plots show velocity changes for new stellar companions. The third row shows trends for new stellar or brown dwarf companions in long-period orbits, while the fourth row shows two new jovian planet candidates. The bottom row shows a known exoplanet with minimum mass 1.1 M_{Jup} in an 11-day orbit, and our discovery of a new exoplanet to the K dwarf HIP 65 with mass 2.9 M_{Jup} in a 1-day orbit (Paredes et al. 2018).

The CHIRON spectra provide a wealth of information that we use to characterize the K-KIDS. **A key goal of our work is to obtain a uniform set of metallicity and age estimates with the same instrument and same zero point. These measurements can then be directly correlated with the companion populations.** The stellar characterization effort is led by graduate student Hodari James, who is exploring the rich CHIRON spectra for metallicity and age indicators, calibrated using cluster K dwarfs. Figure 5 shows just a few of the features that are being investigated, for five K dwarfs with $V - K = 2.45$–3.12. The left panel shows the LiI 6708Å absorption line that can be used to estimate the ages of young K dwarfs in the sample (Soderblom 1990, 1993a, 1993b, 1995), as well as FeI and CaI lines, just a few of the hundreds scattered across the 59 CHIRON orders that can be used to assess metallicity. The right panel shows the CaII 8542Å line that can also be used as an age indicator, much like the classic CaII K/H lines at 3934/3969Å; in this case the younger stars show CaII in emission rather than absorption.

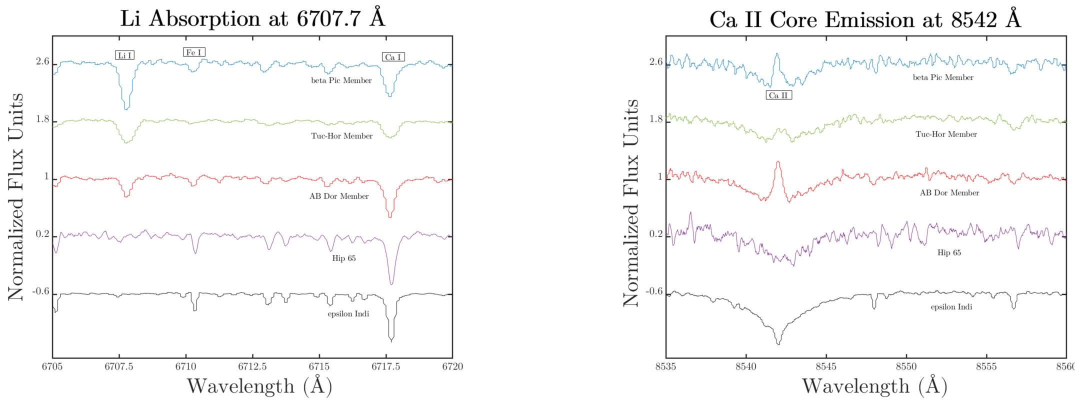

Figure 5: Features found in the K dwarf spectra from CHIRON are shown. (left) The LiI 6708Å line can be used to estimate the ages of young K dwarfs in the sample, as it weakens in example K dwarfs in the β Pictoris (age ∼20 Myr), Tuc-Hor (age ∼40 Myr, broad lines due to rapid rotation), and AB Dor (age ∼150 Myr) groups, to HIP 65 (our planet from *TESS*, see Figure 4) and the nearby K dwarf ϵ Indi (several Gyr). Also evident are FeI and CaI lines, just a few of the many lines that can be used to measure metallicities of K dwarfs. (right) The CaII 8542Å line can also be used to estimate ages, much like the classic CaII K/H lines at 3934/3969Å. In this case, the younger stars show CaII in emission rather than absorption.

7 Broader Impacts: GSU and SCSU — "Sister" Universities

GSU and SCSU both benefit from diverse home cities and student populations to draw upon for the education and public outreach portions of the project. GSU's Atlanta campus has a student population of 32,000, including 42% African-American, 13% Asian, and 10% Hispanic students. SCSU has more than 10,000 students, including 16% African-American, 12% Hispanic, and roughly 5% other non-white ethnicities. The proposed work is truly collaborative, with observation planning, database construction, and K-KIDS publications split between the two groups. Thus, the two institutions would significantly benefit from funding rather than just one. The collaboration has grown so close that Horch joined the broader RECONS group in 2017 and the Physics Masters program at SCSU has become a bridge to the Astronomy Ph.D. program at GSU: Dan Nusdeo finished his degree at SCSU and is now a Ph.D. student at GSU, and Masters student Sam Weiss at SCSU plans to apply to the GSU Ph.D. program for 2019. One of the primary Broader Impacts of the team is providing pathways for minorities to gain science degrees in Physics and Astronomy via Henry's and Horch's efforts to create research opportunities for students with diverse backgrounds — it is more a case of recruiting on the ground rather than applications to formalized programs.

Led by LGBT scientist Henry, the RECONS group at GSU has welcomed 21 undergraduates into the research program, including two African-American men, two Asian-American men, one Hispanic woman and one man, and a total of six women. The diversity tracks to the graduate and postdoc levels, where among the (also) 21 young scientists, there have been one African-American man, one Asian-American woman and two men, three Hispanic men, one transgender man, and a total of six women. Henry is a proponent of getting students to AAS and international conferences "early and often" so nearly every student has been to at least one AAS meeting,[3] as well as to the 0.9m telescope in Chile. Through Henry's SMARTS efforts, 38 young scientists have traveled to CTIO, gaining first-hand observing experience. By various measures, the RECONS effort at GSU has led to student success: seven Ph.D.s and 12 Masters degrees have been earned by students in the group, and 12 different students (including three undergrads) have been first authors on papers in *The Solar Neighborhood* series. Five more students are currently working towards their Ph.D.s.

In the decade that Horch has been at SCSU, the speckle and other interferometry work has involved over 30 students born on all continents except Australia and Antarctica. Of the 25 undergraduate students in the group, seven have been women, including one African-American, one Hispanic-American, two Asian-Americans, and one African. Two of the men are African-American, and one is from South America. Two men and two women were non-traditional undergraduates, returning to obtain their undergraduate degrees after several years in the workforce, and two were veterans of the U.S. Armed Forces. Seven of these students have been co-authors on refereed publications and nine have been either co-authors or the first author on conference presentations. Several have gone on to graduate or professional schools.

Students at GSU and SCSU have excellent opportunities to grow as scientists and engineers, training in areas of broad interest such as electronics, detector technology, statistics, and database construction, as well as the more nuanced specialties of telescope management, astronomical observing, astrometry, photometry, spectroscopy, and interferometry. Every student in both research groups makes astronomical observations, and most travel to observatories — often to Chile, which is typically their first overseas trip. Henry and Horch have proven track records of involving students from underrepresented groups, made possible by the diverse natures of the student populations on both campuses and their concerted efforts to develop inclusive research groups.

We propose specific activities to enhance science and technology careers in Georgia and Connecticut. GSU has a 24in telescope with an Apogee CCD camera at its Hard Labor Creek Observatory (HLCO) one hour east of Atlanta, where observing programs targeting binary stars are underway for students and teachers. The HLCO observations will focus on companions with separations $> 10''$ found in the Wide Survey, with a primary effort to measure the brightness ratios of stars in VRI filters to create RGB images that reveal stellar colors. Students working with Henry will also be engaged in the construction of the RECONS Database, which currently contains over 4000 stars, brown dwarfs, and exoplanets within 25 pc, to which K-KIDS will be added.

At SCSU, outreach will include use of the astronomical observing facility that exists as part of the new science building that opened in 2015, as well as two portable 24in Dobsonian telescopes used to train students working on K-KIDS and for public outreach. Students play active roles in setting up the telescopes, giving tours of the facilities and the sky, and talking with visitors, giving them important experience in science outreach. The SCSU telescopes can also be fitted with the EMCCD detectors that DSSI uses for recording speckle images. When placed on the roof of the new science building, the system can be operated remotely from a third floor observing control room, allowing members to "become professional observers", controlling the camera and the telescope from a computer, taking speckle data, and reducing the data to reveal the binary stars beneath the blur. Students working with Horch devise their own observing programs, carry out high-resolution observations from campus, and contribute measures of binary stars for K-KIDS, thereby contributing directly to our understanding of some of Sun's nearest neighbors.

[3]Henry is also the Chair of the FAMOUS (Funds for Astronomical Meetings: Outreach to Underrepresented Scientists) Grants Program for the AAS.