1 Exploring the Long-Term Behavior of Nearby Red Dwarfs

The solar neighborhood holds a special place in the human psyche because, by our very nature, humans explore the nearest locales first. Space is no exception. The nearest stars provide the framework upon which stellar astrophysics is based because the nearby star population contains the most easily studied representatives of their kinds. The nearest stars also hold the greatest promise for the discovery and detailed characterization of other worlds, and ultimately, any life that may be found on them.

The REsearch Consortium On Nearby Stars (RECONS, *www.recons.org*) was established in 1994 to discover "missing" members of the solar neighborhood and to characterize the complete sample of nearby star systems and their environs. The RECONS hub is now in Atlanta at Georgia State University where the PI of this proposal is a tenured faculty member. To date, RECONS research has been published primarily in a series of 46 papers in *The Astronomical Journal*, beginning with the title *The Solar Neighborhood*.

Here we outline a three-year research plan for RECONS in what is arguably the world's most significant long-term observational effort to characterize red dwarfs, which account for 75% of all stars (Henry et al. 2006, 2018, and updates at *www.recons.org*). The cornerstone of the effort is our astrometry/photometry program at CTIO underway since 1999, which is augmented with observations from other telescopes and deep dives into databases such as *Gaia* and 2MASS. *A key aspect that sets this program apart from other efforts is longevity: after three more years, hundreds of stars will be observed for more than 12 years — the orbital period of Jupiter around our Sun — and more than 100 stars for longer than 20 years.*

With *Gaia* results now in-hand, we are revitalizing RECONS efforts by focusing on two key astrophysics questions, as we continue to explore a sample of red dwarfs in the solar neighborhood. Answering various aspects of these questions is the goal of the Ph.D. thesis efforts of RECONS graduate students Andrew Couperus, Aman Kar, and Eliot Vrijmoet:

- **What are the populations and orbital architectures of companion stars, brown dwarfs, and Jovian planets orbiting red dwarfs on Solar System scales?**

- **What are the long-term magnetic properties and dynamo natures of all types of M dwarfs, and how might photometric variability affect orbiting exoplanets?**

2 Broader Impacts of the RECONS Effort

The RECONS focus on the nearest stars allows us to place our Sun, Solar System, and Earth in context in the cosmos, and makes broader impacts that are both scientific and educational.

1. RECONS provides resources related to the nearest stars. The nearby stars are benchmarks to which any other stellar sample can be compared, and as a group provide a map of exploration for the future. At the RECONS program's website, *www.recons.org*, we provide updated resources for professional and amateur astronomers relating to the nearest stars. The two most popular links are the *Census of Objects Nearer than 10 Parsecs* and the *List of the Nearest 100 Stellar Systems*.[1] The sample of all objects within 5 pc has also been presented by the PI annually from 2010-2020 in *The Observer's Handbook* (e.g., Henry 2020).

2. RECONS teaches a diverse generation of young astronomers astrometric techniques. Astrometry was highlighted in the 2010 Decadal Survey *New Horizons, New Worlds in Astronomy and Astrophysics* as one of the five science frontier discovery areas. Few

[1] As described at http://thebigblogtheory.wordpress.com/2010/10/21/s04e05-the-desperation-emanation/, the RECONS *List of the Nearest 100 Stellar Systems* was used in an episode of the *The Big Bang Theory*.

Ph.D. programs in the U.S. provide opportunities for students to learn astrometric techniques, yet the next few years are critical for teaching astrometry so that young U.S. astronomers will know how to take full advantage of *Gaia* results, and eventually get the most out of the LSST effort at the Rubin Observatory. Members of the RECONS group are steeped in astrometry — the 31 papers in *The Solar Neighborhood* series supported by NSF have been led by 17 different authors, of whom 13 were graduate or undergraduate students. As of 2020, our astrometry program has led to eight Ph.D.s and four Masters degrees, with three more Ph.D. projects underway. We have aggressively recruited students with various backgrounds, including women (Brown, Clements, Gandha, Silverstein, Winters), African-American (Hosey, James, Moore), Asian (Jao, Kar, Patel, Zaman), Latinx (Dieterich, Monteiro, Paredes, Ramos, Rodriguez), LGBT (Vrijmoet), and first generation college students (Ocean, Sevrinsky).

3. RECONS provides opportunities for students to use and build large databases. Since 2003, we have been using data from the SuperCOSMOS Sky Survey (Hambly et al. 2001) that contains 1.9 billion sources to discover nearby stars, and linking the results to other large databases such as ROSAT, GALEX, *Hipparcos*, 2MASS, and *WISE*. In the past three years, every RECONS student has used data from *Gaia* Data Release 2, which contains 1.7 billion sources. Students gain experience with Big Data by (1) creating object samples, (2) cross-matching data from multiple databases, and (3) making follow-up observations from the ground and space. Students are also helping create the RECONS 25 Parsec Database that describes all objects within 25 pc. A working prototype is running internally in Atlanta that includes 4202 stars, brown dwarfs, and planets in 3177 systems, and includes 813 distinct references.

4. RECONS trains students how to run observatories. The CTIO 0.9m remains in operation as part of the SMARTS Consortium only because it is used for the RECONS program described here. It is one of the *very* few remaining telescopes where students can get the full hands-on experience of making observations at a world-class research site. Students also get the opportunity to visit Latin America — for many of the 35 students who have traveled to Chile via our SMARTS work, this was their first overseas trip. In addition, since 2003 the PI has worked with a series of 8 students known as SMARTS Fellows who learn to manage telescope operations and schedule/execute observing programs for users worldwide.

3 RECONS Results from Prior NSF Support

We have made important contributions via a wide range of astrophysical studies under previous NSF support. Our primary observing program has been the astrometry/photometry effort at the CTIO 0.9m that began in 1999 as an NOAO Surveys program and has continued under SMARTS, which the PI helped found in 2003. Additional imaging work has been done on the Lowell 42in, KPNO 0.9m, and Apache Point 0.5m. High-resolution speckle imaging has been carried out at Gemini-N, Gemini-S, SOAR, WIYN, and LDT. Spectroscopic observations have been made on Gemini-S, the CTIO 4.0m, the Apache Point 3.5m, and the CTIO/SMARTS 1.5m. Results are published in *The Solar Neighborhood* series in *The Astronomical Journal*, including 31 papers (those cited in this proposal boldfaced in references) published via a series of the PI's NSF grants from 2005-present. The most recent grant related to the proposed work was *RECONS Explores the Nearest Stars* (AST-1715551, 2017-2020, $496K).

Intellectual Merit

• We have published 25 papers reporting 874 trigonometric parallaxes (813 from the 0.9m and 61 from the 1.5m). We discovered the 20th, 23rd, 26th, 27th, and 42nd nearest stars (all red dwarfs), and a total of 40 new systems within 10 pc (Bartlett et al. 2017; Costa et al. 2005, 2006; Henry et al. 2006, 2018; Jao et al. 2005; Riedel et al. 2011; Subasavage et al. 2009), of which 12 are among the nearest 100 star systems (see *www.recons.org*). We discovered a total of 393 new systems within 25 pc (references above plus Dieterich et al. 2014; Jao et al. 2011, 2017; Riedel et al. 2010, 2014, 2018; Subasavage et al. 2017; Vrijmoet et al. 2020; Winters et al. 2017). Many of these are the southern red dwarfs in the SURVEY sample that form the core for the proposed science discussed below (§5.1 and Figure 1, left).

• We have discovered 48 new white dwarfs within 25 pc (Subasavage et al. 2017), a horizon within which only 99 were previously known. We discovered 16 rare, cool subdwarfs within 50 pc (Jao et al. 2005, 2011, 2014, 2017), including the third and fourth nearest, and revealed the nearest pre-main sequence star and 35 more nearby young red dwarf systems (Riedel et al. 2011, 2014, 2018), most of which are members of young associations, but a few that are "rogue" young stars. We also published parallaxes for 37 red/brown dwarfs that straddle the stellar/substellar border (Dieterich et al. 2014) that were used to determine the border between the lowest mass star and highest mass brown dwarf.

• We have published 28 papers reporting VRI photometry for more than 1000 stellar systems. In particular, we give VRI for 799 systems in Winters et al. (2015), in which we identified a total of 1404 red dwarf systems within 25 pc in the southern sky. This remains the largest compilation of VRI photometry for nearby southern red dwarfs.

• We have provided tools for astronomers worldwide, including the mass-luminosity relation for red dwarfs (Henry et al. 1999, Benedict et al. 2016), photometric distance relations (Hambly et al. 2004; Henry et al. 2004), the overall census of nearby stars (Henry et al. 2006, 2018, and at *www.recons.org*), and methods to find hidden binaries in *Gaia* data (Vrijmoet et al. 2020).

Broader Impacts

Through this work, we are developing the most comprehensive view of the solar neighborhood ever achieved, as evidenced by the large numbers of new discoveries so close to the Sun. We have studied red dwarfs that are young, on the main sequence, and old, thereby spanning the Milky Way's entire history. We have examined stars that have evolved into white dwarfs, and the brown dwarfs that did not reach stardom. Significant effort has gone into understanding the luminosity and mass functions (Henry et al. 2006, 2018; Winters et al. 2015, 2019) and measuring reliable masses for the most common objects in the Universe, the red dwarfs (Benedict et al. 2016). Since first being funded by NSF in 2005, there have been 4–8 students in the RECONS group, each of whom has learned astrometric and photometric techniques, and oftentimes spectroscopic techniques as well. Overall, the results of RECONS' exploration of the solar neighborhood have provided fundamental data used by many other astronomers for stellar and exoplanet studies, as well as the public. One specific example of public engagement is particularly cogent — the *RECONS 25 Parsec Database* movie has been viewed more than 19000 times (see *https://www.youtube.com/watch?v=up_MqNBv0FE*).

4 Synergy with *Gaia* Results

In April 2018, *Gaia* Data Release 2 (DR2) provided results for 1.7 billion sources (Gaia Collaboration 2018). The timing of this proposal is auspicious because Early Data Release 3 (EDR3) is due in December 2020 and the full DR3 is slated for 2022. Our astrometry experience allows us to probe deeper into the *Gaia* results than most astronomers are likely to, as evidenced with two illustrative examples for objects within 10 pc: (1) DR2 yields 1722 entries with parallaxes of 100 milliarcseconds (mas) or more, but only 304 (18%) are real primaries or secondaries, plus an additional 39 candidates. The remaining 1379 (80%) are not real, typically because of corruption by nearby sources. The *Gaia* project has offered two methods to scrub such samples, but careful crosschecking indicates that both methods eliminate real objects. (2) DR2 omits 52 (16%) of the 309 systems known within 10 pc. These are too bright (Vega), too faint (brown dwarfs), too fast-moving (Wolf 359), known close binaries (SCR 1546-5534AB), and the occasional star for which there is no obvious explanation (LHS 3746).

Every point in *Gaia* is bright enough to be observed on 1m class telescopes. This is important because we can create carefully-vetted, volume-complete samples to understand, *statistically*, what fractions of red dwarfs have companions in certain types of orbits and how often they change brightness on various timescales. EDR3/DR3 should improve upon DR2 results, thereby leading to statistically improved samples, yet work will remain to be done on sources with poor, incorrect, or missing solutions. Compelling research areas remain for RECONS' targeted program in the era of *Gaia* because of three distinct observational advantages:

1. Longevity — Our long-term astrometric and photometric studies have a 15-year head start on *Gaia* because *Gaia's* first data were taken in 2014. *Gaia* has been approved through the end of 2022, extending its observing baseline to 8 years; by then we would have up to 23 years of data on hundreds of the nearest red dwarfs. We map orbits of companions that take decades to orbit their primaries (§5.3.1), and are finding that the smallest stars exhibit long-term stellar cycles like the Sun much longer than any *Gaia* dataset (§5.4.1). Ultimately, we can combine our datasets with *Gaia's* to strengthen the results of both.

2. Cadence Flexibility — As operators of the 0.9m, we can schedule observing runs as needed. For orbits, we optimize observations to concentrate on periastron passages and on fast-orbiting systems with periods as short as a few months, while for the variability work, we can use the 0.9m to determine rotation periods via high-cadence hourly and nightly observations.

3. Resolution — We resolve companions in a long-term program at SOAR (§5.3.2) at much closer separations than *Gaia* can. Careful inspection of the 35 red dwarf binaries in the 10 pc sample with separations $\leq 2''.0$ indicates that only two are resolved in *Gaia* DR2, at separations of $1''.32$ and $1''.58$. Two typical red dwarfs with masses of 0.4 $M_{\odot}$ and 0.2 $M_{\odot}$ separated by 5 AU will orbit one another in 14.4 years and will be only $\sim 0''.3$ apart at 16.6 pc, the edge of our SURVEY core sample. Such a system is not resolved by *Gaia*.

5 Research Goals for 2021-2024

Our goals are driven by the desire to characterize the long-term behavior of red dwarfs, which account for three of every four stars. The key to this work is that we have substantial datasets on hundreds of red dwarfs that reach back to 1999 that allow us to carry out unique science over unprecedented timescales. Because we have a stable, long-term observing program that provides both astrometric and photometric data, and deep knowledge of the red dwarf population, we are positioned to reach the proposed goals by 2024. The primary research goals for the proposed work over the next three years are:

Goal 1: Take a census of stellar/brown dwarf/Jovian companions with orbital periods of up to 30 years around at least 500 nearby red dwarfs. We will then understand the outcomes of formation scenarios for the three different classes of companions on Solar System scales. [Ph.D. work of Eliot Vrijmoet]

Goal 2: Evaluate long-term starspot cycles on a large sample of red dwarfs for the first time, and correlate the results with stellar rotation to reveal and constrain underlying magnetic dynamo behaviors. Samples of twin red dwarf binaries and the nearest red dwarfs reported to have exoplanets will also be scrutinized. [Ph.D. work of Andrew Couperus and Aman Kar]

5.1 The SURVEY Sample and Enhancements

Our science investigations focus on a carefully vetted core sample of the nearest 466 red dwarfs in the southern sky known as the SURVEY sample. To provide robust statistics, we use a volume-limited, complete set of red dwarfs that are simultaneously observed both astrometrically and for relative photometry. The SURVEY sample has been created using the RECONS team's detailed knowledge of red dwarfs in the southern sky developed over the past 20 years, augmented with *Gaia* DR2 results (to be updated with EDR3 and DR3). These stars (a) are red dwarf primaries, (b) have trigonometric parallaxes of at least 60 mas (16.7 pc), and (c) are south of DEC = 0 at all RA. Conveniently, nearly all red dwarfs of spectral type M fall within a factor of eight in mass from 0.075–0.60 $M_\odot$, which allows us to subdivide the sample in to three groups differing by factors of two in mass. These subsamples are dubbed Blue/Green/Red M dwarfs, and are outlined in Table 1 and color-coded on an observational H-R diagram in Figure 1 (left).

Table 1: Red Dwarfs in the SURVEY Sample

Subsample	Mass Range	M_{BP}	M_V	M_K	$(BP-K)$	$(V-K)$	Spectral Type
Blue	0.60–0.30 $M_\odot$	9.31–12.09	9.03–11.84	5.32–7.03	3.99–5.05	3.71–4.80	M0.0–M2.5V
Green	0.30–0.15 $M_\odot$	12.10–14.15	11.85–13.90	7.04–8.30	5.06–5.84	4.81–5.59	M3.0–M5.5V
Red	0.15–0.075 $M_\odot$	14.16–19.50	13.91–19.32	8.31–10.07	5.85–9.42	5.60–9.24	M6.0–L2.0V
Brown	< 0.075 $M_\odot$	> 19.50	> 19.32	> 10.07	> 9.42	> 9.24	> L2.0V

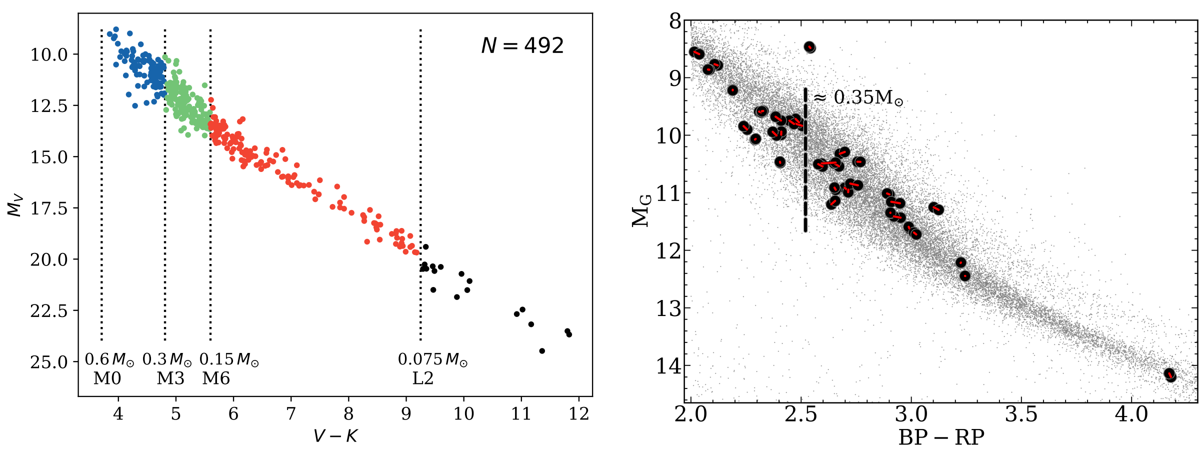

Figure 1: Two samples of red dwarfs explored in the proposed work are shown: (left) The SURVEY sample observational H-R diagram, with M_V representing luminosity and $V-K$ temperature. The three subsamples of M dwarfs — Blue, Green, and Red — are color-coded; substellar brown dwarfs are plotted with black points. Dotted lines indicate mass cutoffs determined using the RECONS mass-luminosity relations of Benedict et al. (2016), with corresponding spectral types. (right) The TWINS sample observational H-R diagram, with M_G representing luminosity and *Gaia* $BP-RP$ temperature. Black points indicate the components of 36 binary pairs within 50 pc, with components connected by red lines. The elevated pair is 2MA0201+0117AB, a young β Pic binary at 49 pc (Alonso-Floriano et al. 2015). The vertical line roughly marks the division between partially radiative and fully convective red dwarfs. Background points are stars within 50 pc from *Gaia* DR2 illustrating the main sequence.

While precise mass borders are confounded by stars with varying metallicities, ages, and magnetic properties, these subsamples are certainly representative of three categories of M dwarfs: (1) Blue — 151 stars that are partially radiative and show relatively weak TiO bands, (2) Green — 168 stars that are fully convective with modest TiO, NaI, and CaII absorption features, and (3) Red — 147 stars that stretch to the end of the stellar main sequence, are fully convective, and exhibit strong TiO, NaI, and CaII absorption, as well as VO features. With these carefully designed subsamples, we will be able to compare the three types of red dwarfs, e.g., discern any differences in the sizes and shapes of orbits for primaries spanning a factor of eight in mass. Because the sample is an effectively complete census of the nearest red dwarfs that requires negligible corrections, we will also be able to provide statistically robust results, such as the fractions of stars in subsample that exhibit stellar cycles. Because of its careful construction and vetting, the SURVEY sample will be a bedrock sample that can be used in the decades to come for studies beyond those proposed here.

We enhance the SURVEY sample with four smaller sets of captivating targets; these will not be included in statistical results but have specific applications. (1) To enhance the orbits work, we include 43 (so far) additional red dwarf binaries out to 25 pc for which we have already detected photocenter shifts in 0.9m astrometric data. (2) For both the orbits and variability efforts, we include a set of 29 nearby brown dwarfs for comparisons to low mass star results — some shown as black points in the left panel of Figure 1 (not all have V photometry). (3) We observe 36 sets of red dwarf "twin" binaries within 50 pc having magnitudes and colors that match to within 0.1 mag at optical and near-infrared wavelengths. These TWINS are shown in the right panel of Figure 1, and will be used to determine whether or not stars of the same luminosity, temperature, mass, metallicity, and age have similar magnetic properties. (4) We focus on a set of 45 (so far) red dwarfs within 25 pc with known exoplanets to determine the flux variations on their planetary environments.

5.2 The CTIO/SMARTS 0.9m

We have used the 0.9m since 1999, initially during a three-year NOAO Surveys program that has continued via SMARTS since 2003. To date, eight students in the group have used the 0.9m to complete their Ph.D. work, and three more (Couperus, Kar, and Vrijmoet) are using the telescope now. The 0.9m and its CCD camera have proven to be a durable, reliable combination where we have observed for more than 1600 nights without losing a full night to telescope problems — weather, computers, camera, yes ... but telescope, no. For RECONS, the telescope/camera combination has provided excellent astrometry and photometry for red and brown dwarfs, white dwarfs, subdwarfs, young stars, and asteroids.

We are currently observing 733 targets during ∼80 nights/year, using the CCD camera with a 13$'$6 field and 401 mas pixels on the sky for both differential astrometry and photometry. Red/brown dwarfs with VRI = 9–20 are observed, selecting the appropriate filter for objects to match reference star configurations and to provide ideal exposure times of 30–600 seconds/frame. We typically have 6–8 observing runs per year, during which visits comprised of 3–5 good frames yield nightly mean positions accurate to 1–5 mas, and resulting parallaxes with errors of 1 mas, and proper motions good to <1 mas/yr. Because the PI operates the 0.9m for SMARTS, we can schedule observing runs to maximize the science, such as increased cadence for short orbits or rotation periods.

The same images used for astrometry are used to measure absolute photometry to 0.03 mag, and relative photometry to 7 millimagnitudes (mmag) in focused images and 2 mmag in defocused images. Absolute photometry relies on photometric standards, while for relative photometry the target's flux is compared to the fluxes of photometrically quiet reference stars using the methodology outlined in Jao et al. (2011) and Hosey et al. (2015). We control for changes in seeing, airmass, and atmospheric transparency in the images by utilizing the prescription discussed in Honeycutt (1992).

5.3 Goal 1: Formation of Stars, Brown Dwarfs, and Giant Planets

What are the populations and orbital architectures of companion stars, brown dwarfs, and Jovian planets orbiting red dwarfs on Solar System scales? (Vrijmoet)

To answer this question, we will provide a portrait of the stellar/brown dwarf/Jovian planet formation process through a systematic census of companions orbiting the ∼500 stars in the

SURVEY sample (§5.1). We will evaluate both the numbers of companions and their orbital architectures, and compare the results to theoretical work (e.g., Bate et al. 2009, 2012). The key research driver is the development of an orbital period (P_{orb}) vs. eccentricity (e) diagram — stars presumably form in pairs without a strong preference for orbital eccentricity, while planets likely form in disks that result in (usually) circular orbits. There are few examples of fully-mapped orbits for red+brown dwarf systems, so their orbital architectures are unclear, an issue we hope to remedy. We will (1) systematically survey many more stars than previous efforts, (2) canvass for stellar, brown dwarf, and some Jovian companions, and (3) merge our results with those from radial velocity (RV) and transit work to extend our comparisons all the way down to Jovian planet masses, and beyond. Critically, in searching for companions astrometrically, we are sensitive to mass rather than luminosity, so avoid the many challenges of imaging faint secondaries at separations less than $1''$.

Many searches have been done for close companions to *nearby* red dwarfs, stretching back to Henry (1991, 74 stars, infrared speckle), followed by Fischer & Marcy (1992, 62 stars, RVs), Delfosse et al. (1999, 127 stars, RVs), Bergfors et al. (2010, 124 stars, lucky imaging), and Ward-Duong et al. (2015, 245 K and M stars), among others. These studies revealed stellar companions but were not sensitive to brown dwarfs (imaging) or beyond periods of a few years (RVs), and rarely pushed to determine orbits for periods longer than 3 years. It is currently unclear what orbital architectures for companions to red dwarfs look like out to P_{orb} = 30 yr, roughly Saturn's orbital period in our Solar System. Nor is it known what the suite of red+brown dwarf orbits looks like: perhaps they form like stars, but the 2% rate at which brown dwarfs are found orbiting red dwarfs (Dieterich et al. 2012, 126 stars) is far below the rate of 10% found for Jovian planets (Bonfils et al. 2013, 102 stars), and nowhere close to the 27% fraction of stellar secondaries (Winters et al. 2019, 1120 stars, primarily wide companions).

Efforts to model stellar binary formation focus on either turbulent core fragmentation (Fisher 2004; Offner et al. 2009), disk fragmentation (Kratter et al. 2016; Zhao et al. 2020), or dynamical capture (e.g., Moeckel et al. 2010), but the full story likely involves a combination of all three scenarios (Lee et al. 2020). A realistic combination is difficult to explore computationally due to the vast ranges of scales involved, as the gas dynamics that dictate each protoplanetary disk's propensity for fragmentation occur on sub-AU scales, while simultaneously each of that system's neighbors in its nascent cluster interacts dynamically on thousand-AU scales. Bate (2012) has presented a set of simulated multiples' orbits, but the P_{orb} vs. e distribution for 46 systems lacks some remarkable features of its observational counterpart in Raghavan et al. (2010), which included 127 solar-type multiples. It notably misses the circularized orbits observed for systems with short orbital periods attributable to tidal circularization, a discrepancy caused by the use of point particles to approximate collapsing gas cores on 0.5 AU scales.

Dynamical interactions also shape an upper envelope in P_{orb}–e space in the empirical dataset for solar-type stars, and create a distribution that lacks many systems with $e \leq 0.2$ for P_{orb} = 100–10000 days. Both effects appear to be in play for red dwarf systems as well, as hinted at in preliminary results by Udry et al. (2000), and in our initial, but more extensive, results shown in the left panel of Figure 3 for 99 red dwarf binaries (roughly half from RECONS and half from the literature). For reference, a binary made up of the most massive (0.60 $M_\odot$) and least massive (0.075 $M_\odot$) stars in our survey in 3-year and 30-year orbits would have semimajor axes of 1.8 and 8.5 AU, respectively.

There are several intriguing features of this initial diagram. First, for P_{orb} = 0–3 years, there are many nearly circular orbits, but none with $e \geq 0.6$. Second, for P_{orb} = 3–10 years, there is a dearth of nearly circular orbits with e = 0.0–0.2 (outlined with the dotted box). Third, and most surprising, there are currently *zero* nearly circular orbits with e = 0.0–0.2 in the sample for P_{orb} = 10–30 years (shown with the orange box). These initial results imply that the star formation process does not produce red dwarf binaries separated by ≤2 AU in highly eccentric orbits, and rarely, if ever produces binaries in circular orbits at separations of ∼2–9 AU. These distributions are not clear among the lower mass (≤0.1 $M_\odot$) sample of Dupuy & Liu (2017), suggesting, perhaps, different disk lifetimes for stars vs. brown dwarfs — but again, more red+brown dwarf orbits are needed.

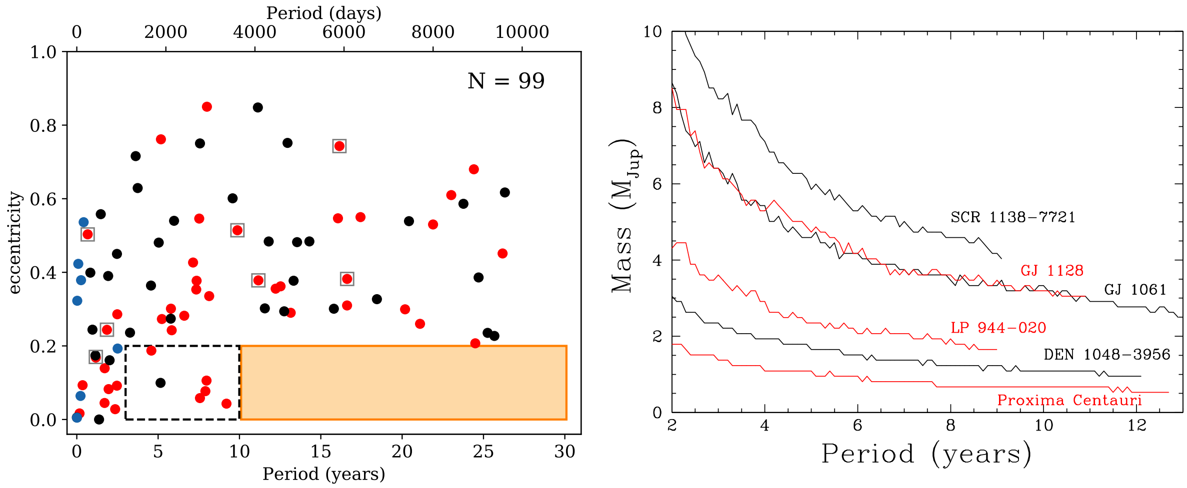

Figure 2: Two RECONS companion search results: (left) Initial results are shown for 99 red dwarf binaries in the orbital period vs. eccentricity diagram. Red points indicate systems from RECONS work (boxed points are orbits shown in Figure 3), black points are from the literature, and blue points are from radial velocity work. The dotted box outlines a curious dearth of circular orbits for P_{orb} = 3–10 yr and the orange box highlights a "zone of avoidance" where low mass stellar multiples do not seem to form at all. Points representing systems with $P_{orb} \leq 3$ yr generally have errors in P_{orb} and e smaller than the points, while the errors are sometimes significantly larger for points for $P_{orb} \geq 10$ yr. (right) Limits for Jovian planets orbiting nearby stars. Lines trace the mass limits for planets that would have been detected 90% of the time orbiting six red dwarfs, determined by simulating millions of orbits with various orientations on the sky and comparing to our astrometric series — planets above the lines would have been detected. There is no Jupiter orbiting Proxima Cen with P_{orb} = 4–12 yr (Lurie et al. 2014).

To reveal the details of star formation, we would like to populate the P_{orb}–e diagram more completely. Imagine the left panel of Figure 2 carved into 30 boxes that each have a width of 5 years in period and a height of 0.2 in eccentricity. **Our goal is to derive orbits for at least 150 binaries. If the star formation process is random, we would find 5 points in each box, but already it seems that this is not the case.** Clearly, additional orbits are still needed with P_{orb} longer than 10 years — this is the regime where our long-term astrometry program is most powerful, and our datasets will continue to improve via this proposal through 2024, thereby boosting the number of long-period orbits.

Because of the longevity of our astrometry program, we are also able to explore the nearby stars for Jovian planets in Jupiter-like orbits. Figure 2 (right) illustrates our detection limits for six stars observed for at least 9 years (Lurie et al. 2014). Curves mark the mass points at which 90% of millions of simulated orbits are inconsistent with the data, i.e., above these lines we would detect nearly all companions. None of these six stars have brown dwarf companions with masses down to 13 M_{Jup}, and we can rule out most Jovian planets for periods longer than 2 years. We find that Proxima Centauri has no companions more massive than 2 M_{Jup} with periods longer than 2 years, nor a 1 M_{Jup} Jupiter twin for periods longer than 4 years. As observations continue, the curves not only stretch to the right, but continue to descend because short-period companions continue to be eliminated as more cycles of an orbit fail to fit the astrometric residuals. We are most sensitive to companions in long-period orbits up to the full duration of the observations, complementary to radial velocity surveys that are most sensitive to hot Jupiters in short-period orbits. It is clear that stellar and brown dwarf companions are well within the reach of our astrometric survey, and that we reach down to a few Jupiter masses for many stars. Nonetheless, we will take advantage of Jovian detections from radial velocity searches to boost the number of Jovian planets in our analysis.

Henceforth, improvements in computational resources will make approximations such as those used in Bate (2012) less necessary, thereby increasing the need for comprehensive observational studies against which such results can be compared. Our astrometric survey is sensitive to companions with masses spanning a factor of 500, from stellar companions with masses of 0.5 $M_\odot$ down to Jovian planets with masses of 1 M_{Jup} in orbital periods up to 30 years.

5.3.1 Astrometric Perturbations with the CTIO/SMARTS 0.9m

Our companion search builds on a long-term investment of high-quality data already in-hand from the 0.9m. With an observing cadence of 3–6 times/year, we are typically sensitive to companions with orbital periods as short as 1 year, after solving for parallaxes and proper motions. Of the 466 stars in the SURVEY sample, 130 have been followed for 0–3 years, 30 for 3–6 years, 68 for 6–9 years, 50 for 9–12 years, and 188 for more than 12 years. All stars will be observed, but via this proposal we will concentrate on two key groups: the 160 stars with less than 6 years of coverage and the dozens of stars with partial orbits.

Shown in Figure 3 are results for four red dwarf binaries for which we have mapped full orbits using the 0.9m. This is a small subset of the 134 systems for which we have already detected astrometric perturbations, including 36 that already have complete orbits. Most of these are stellar companions, but a few have already been imaged and found to be brown dwarfs, e.g., SCR1845-6357B by Biller et al. (2006). In many cases, no resolution has yet been accomplished via any program — we estimate that at least 10 companions in our sample are brown dwarfs because resolution attempts have so far failed. These will be key in our comparison of star+star vs. star+brown dwarf orbital architectures. **Note that the secondary does not have to be imaged for us to derive orbital periods and eccentricities, as these two quantities are identical for photocentric orbits of unresolved systems and resolved orbits.**

For $P_{orb} \geq 10$ years, orbits can only be mapped via a long-term program like ours. *Gaia* will detect companions with orbital periods of 0.2–4 years around *some* M dwarfs (Sozzetti et al. 2013), but careful inspection of *Gaia's* expected sensitivity shows that the sample is heavily tilted towards the late K and early M dwarfs, i.e., our Blue subsample, which can be surveyed to more sensitive limits using radial velocities. Ultimately, the upper limit in orbital periods effectively sampled by *Gaia* will be set by the mission lifetime; at best *Gaia* will reach to 10 years, at which point the spacecraft will run out of micro-propulsion fuel. We have already pushed beyond 10 years for more than 200 stars, and will continue to extend the coverage.

For $P_{orb} \leq 3$ yr, radial velocity efforts provide some orbits (blue points in Figure 3). The two largest high-precision radial velocity surveys of M dwarfs published to date are those by Endl et al. (2006, 90 stars) and Bonfils et al. (2013, 102 stars). These surveys, and the ongoing CARMENES effort (Reiners et al. 2018, 324 M dwarfs), typically drop binaries from their observing lists and concentrate on massive red dwarfs that only account for about one-third of all red dwarfs. Virtually all of the M dwarfs in the radial velocity surveys are in our Blue subsample, so the bulk of our survey explores uncharted territory. Of course, we will incorporate all stellar, brown dwarf, and planetary companions found via radial velocity programs into our analysis. To boost the number of short-period orbits, we are carrying out a high-resolution speckle imaging program at SOAR.

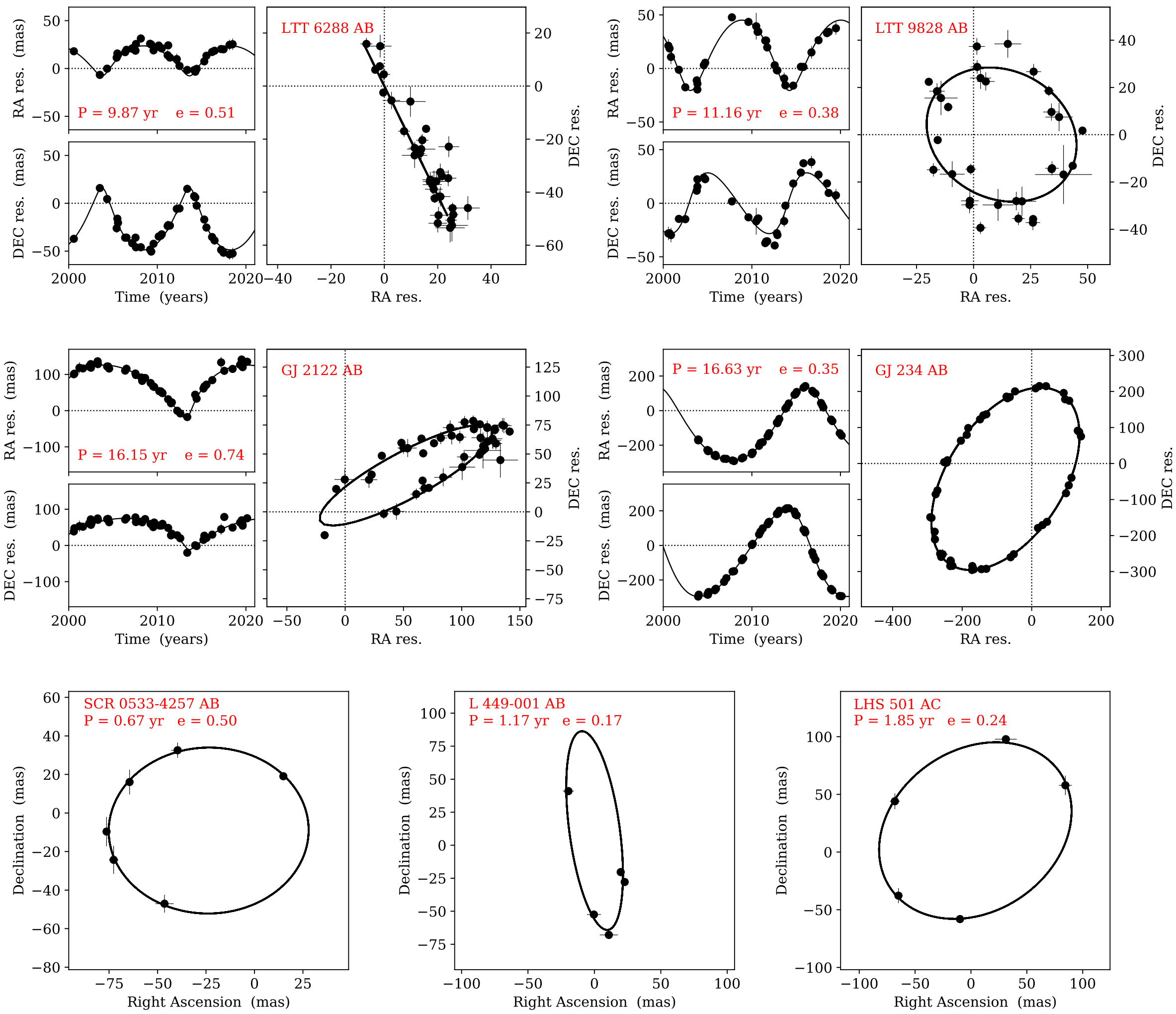

Figure 3: The top four sets of plots illustrate photocentric orbits for binaries with periods of 9.8–16.6 yr measured at the 0.9m. The astrometric residuals in milliarcseconds (mas) in the RA and DEC axes are shown to the left, after solving for parallax and proper motion, and the resulting orbit is plotted on the right. Each point represents typically 5 frames taken on a single night. All binaries here have fully wrapped orbits and solutions with orbital periods and eccentricities in the corners. Dozens more orbits have wrapped in our datasets, while others need more coverage. The three bottom plots show relative orbits for red dwarf binaries with short periods of 0.7–1.9 yr determined during our SOAR speckle program.

5.3.2 High-Resolution Imaging with SOAR

To increase the number of orbits with $P_{orb} \leq 6$ yr, we are carrying out an optical speckle imaging program at the SOAR 4.1m awarded long-term status by NOIRLab as part of Vrijmoet's Ph.D. effort. The program is already yielding results — the three orbits with P_{orb} = 0.7–1.9 yr shown at the bottom of Figure 3 are from SOAR data (they were initially known to have companions from 0.9m observations). We are using HRCam+SAM to observe 335 stars brighter than $I = 14$ in the SURVEY and enhanced samples. Included in the target list are red dwarfs within 25 pc in *Gaia* DR2 that we suspect are new multiples using astrometric criteria determined by comparisons to our 0.9m results for single and double red dwarfs (Vrijmoet et al. 2020). We have teamed up with Andrei Tokovinin at CTIO, the inventor and Instrument Scientist for the SOAR Adaptive-Optics Module (SAM). This provides scheduling flexibility, as time awarded to Vrijmoet and Tokovinin is shared to maximize the orbital coverage of binaries. To date, we have observed 270 stars at SOAR and 160 have been resolved, with separations of 35 mas to 3.″2 and brightness differences ranging from 0.0–5.0 mag at I. If a companion is detected, the system is observed at V to determine the components' colors. Non-detections are quite valuable, as flux limits determine what type of companion has *not* been seen — if a *stellar* secondary is eliminated, the companion must be a brown dwarf or Jovian planet.

The 0.9m data allow us to measure the parallaxes, proper motions, and photocentric orbits that map the motion of the center of light for each two-body system. We use HRCam+SAM on SOAR to resolve the systems, which allows us to (1) measure flux ratios so that we can determine what type of companion is there, (2) scale our photocentric orbits to the relative orbits of the components, (3) refine the critical P_{orb} and e values, and (4) in combination with the 0.9m data, determine mass ratios and individual masses (there is no $sini$ uncertainty like that for radial velocity orbits). These masses can be used to expand upon our mass-luminosity work presented in Benedict et al. (2016) that included 47 M dwarfs with masses of 0.08–0.62 $M_{\odot}$. Assuming that we resolve only two-thirds of the 150 systems with reliable orbits from the orbital architectures project, we will have 200 points (2 stars per system) for an updated mass-luminosity relation. Such a large number would allow us to investigate second-order effects such as metallicity, age, and magnetic activity that affect the luminosities of stars of similar masses.

5.4 Goal 2: Magnetic Properties of Red Dwarfs

What are the long-term magnetic properties and dynamo natures of all types of M dwarfs, and how might photometric variability affect orbiting exoplanets? (Couperus and Kar)

To answer these questions we will investigate the photometric variability of the SURVEY and enhanced samples of red dwarfs. Our assumption is that photometric variability is a proxy for magnetic fields that cause flaring and create spots, leading to changes in measured brightnesses over time. Of principle interest are long-term spot cycles similar to the 11-year solar cycle and medium-term brightness modulations due to spots that rotate in and out of view. Our ultimate goals are to (1) characterize photometric cycles that are presumably manifested because of magnetic dynamos, (2) link these cycle results to rotation periods to constrain red dwarf dynamo theory, (3) determine representative statistics for stellar cycle properties, (4) inform the predictability of red dwarf magnetic activity via twin star examinations, and (5) examine how this magnetic activity might affect orbiting exoplanets.

5.4.1 Long-Term Spot Cycles and Magnetic Dynamos

The unique aspect of our effort is the long-term study that reveals starspot cycles on red dwarfs. We use the same VRI images acquired at the 0.9m for the astrometric study outlined above to explore an aspect of red dwarfs that may prove crucial to potential life on any orbiting planets — the consistency in the flux provided by the stars, i.e., the stellar variability induced by magnetic activity. We build upon our work presented in Hosey et al. (2015) and Clements et al. (2017) that focused on overall variability, not cycles. We have already identified ∼20 new confident cycles and several dozen candidate cycles across the M dwarf spectral sequence. A treasure trove of RECONS data has yet to be examined in detail, with additional cycles likely awaiting discovery. We show four examples of what we interpret to be starspot cycles in Figure 4, with periods of 6–29 years and amplitudes of 25–67 mmag. In particular, WT460AB showcases remarkable new observational territory given a cycle lasting nearly three decades, a result that is only attainable through a long-term program like ours.

Previous efforts have examined samples of M dwarfs at optical wavelengths in smaller numbers or over shorter time periods. In his classic study, Weis (1994) reported photometric measurements of 43 stars over an 11 year period, and found perhaps two stars with periodic cycles

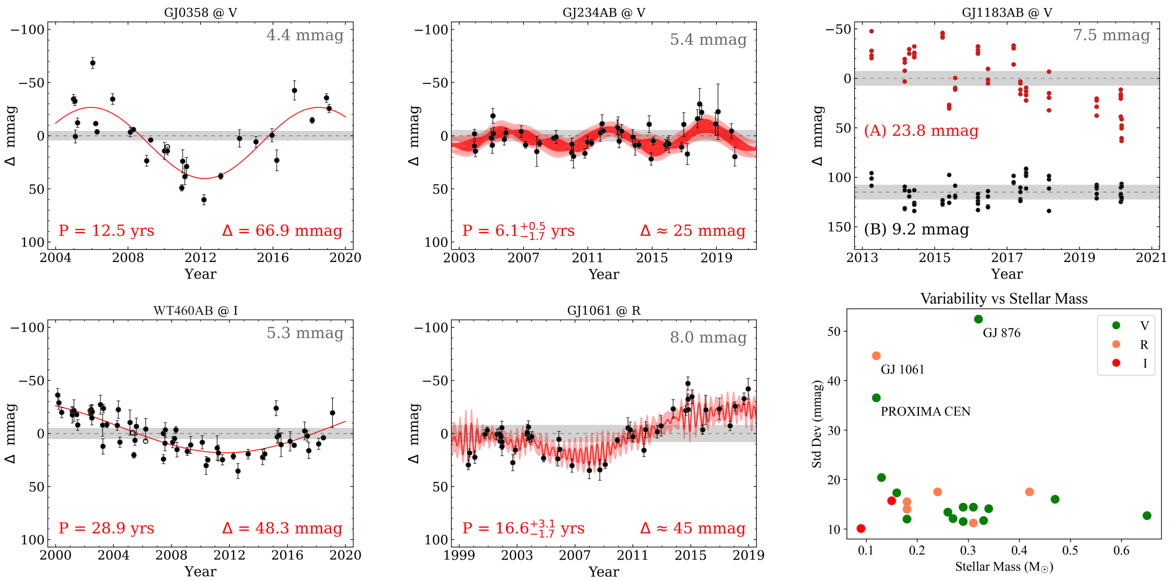

Figure 4: Photometric variability results are shown for red dwarfs on the 0.9m program. The four light curves (a star moves up on the plot when it grows brighter) in the left and center have points that represent means of typically five images taken on a night, while the top right panel has a point for each frame. Gray regions indicate the variability range of the reference stars in millimagnitudes (mmag) used for comparison in each field, with values of 4.4–8.0 mmag given in gray in the upper right of each panel. The two left panels show curves representing spot cycles for GJ 358 and WT 460AB using straightforward Lomb-Scargle fits. The two center panels show curves for GJ 234AB (P_{rot} = 1.58 days) and GJ 1061 (P_{rot} = 143 days) with Gaussian Process fits that include rotation analyses, varying cycle amplitudes, and errors on the periods. The cycles last for 6–29 years at amplitudes of 25–67 mmag, or ∼3–7% in flux. The top right panel shows light curves for both components of a wide binary in the TWINS sample, GJ 1183AB — although the two red dwarfs are virtually identical in mass, composition, and age, they exhibit very different photometric variations over 7 years. The bottom right panel shows first results for 22 red dwarfs with exoplanets, three of which show high levels of photometric variability at optical wavelengths.

lasting less than 3 years. There are now a few tens of cycles known for partially radiative red dwarfs, but only ∼15 cycles for fully convective stars (references below). To boost the number of measured cycles and to derive reliable statistics, we are observing the ∼500 SURVEY stars to map variability at a cadence of 3–6 visits/year with a "variability floor" of 7 mmag.

Current theoretical understanding of red dwarfs is markedly unsettled, as evidenced in part by the struggle to predict even accurate stellar radii (Parsons et al. 2018; Morrell & Naylor 2019). Cycle length predictions for red dwarfs are limited and significantly uncertain, with estimates ranging from a few years up to several decades or longer (Fan & Fang 2014; Shulyak et al. 2015; Küker et al. 2019), and there is no present consensus for dynamo models (MacDonald & Mullan 2014; Shulyak et al. 2015), demonstrating that theoretical efforts require observational guidance. Red dwarf dynamo investigations fall under two domains — partially radiative and fully convective stars. In each case, there is also evidence for an additional dynamo division between rapidly and slowly rotating stars (Brandenburg et al. 1998; Böhm-Vitense 2007; Donati et al. 2008; Yadav et al. 2016). There is much debate between competing dynamo explanations in *all* of these cases. For partially radiative red dwarfs, conventional dynamo wisdom and rotation-activity relations suggest a solar-like dynamo (Wright et al. 2011; Newton et al. 2017), whereas the stellar cycles known for these stars have suggested turbulent (or otherwise non-solar) dynamos (Savanov 2012; Vida et al. 2014; Suárez Mascareño et al. 2016; Küker et al. 2019). Conventional thinking and magnetic topology observations suggest a transition in dynamo type at the onset of full convection (Donati et al. 2008; Morin et al. 2008), whereas rotation-activity relations again suggest either solar-like or otherwise dynamo-independent results (Newton et al. 2017; Wright et al. 2018). To complicate matters further, rapidly rotating fully convective M dwarfs demonstrate strong evidence for a possible bi-stable dynamo under which similar stars can host either of two dynamo states depending on variations in the stellar initial conditions (Morin et al. 2010; Gastine et al. 2013; Kochukhov & Lavail 2017; Shulyak et al. 2017, 2019). However, this may instead be a cyclical dynamo observed during transition phases similar to the solar cycle inversion (Kitchatinov et al. 2014).

To navigate this complex landscape, *many* observational and theoretical efforts have emphasized a critical need for long-term observations spanning many years to decades (Brown 2014; Gunning et al. 2014; Kitchatinov et al. 2014; Oláh 2014; Shulyak et al. 2015, 2017; Suárez Mascareño et al. 2016; Yadav et al. 2016; Wargelin et al. 2017; Lavail et al. 2018; Ibañez Bustos et al. 2019; Bondar' 2020; Muirhead et al. 2020). We propose to obtain the long-term cycle data across the full range of red dwarfs, to reveal (1) the presence (or lack thereof) of such cycles, indicating dynamos that are (or are not) oscillatory in nature, (2) the periods and amplitudes for detected cycles, thereby offering clear observables for models to reproduce, (3) the slope of a $log(P_{cyc}/P_{rot})$ vs. $log(1/P_{rot})$ diagram, to be used to evaluate the so-called Dynamo Number (Baliunas et al. 1996), a valuable diagnostic for differentiating between dynamo states via trends between rotation and cycle length. It has been minimally explored for M dwarfs (Savanov 2012; Vida et al. 2014; Suárez Mascareño et al. 2016), and never for fully convective stars exclusively — we will do this for the first time (Couperus et al. in prep).

There are two key aspects of our proposed work that will lead to fundamental breakthroughs in understanding magnetism and dynamos in red dwarfs. First, the longevity of our 0.9m observing program surpasses existing efforts that have been largely limited to $<$ 10 year baselines, allowing us to sample different parameter regimes of stellar dynamos. Most known M dwarf cycles reported to date are from ASAS-3 (2000-2009) or *Kepler* (2009-2013) (Savanov 2012; Vida et al. 2014; Arkhypov et al. 2015; Suárez Mascareño et al. 2016), but the observed cycles have typically markedly shorter periods than predicted (Küker et al. 2019). Our extended datasets will lead to detections of longer period cycles, thereby helping constrain cycle length predictions overall, and can also obtain cycle repeats (e.g., GJ 234AB in Figure 4).

Second, we are using a robust analysis method to model activity cycles that are quasi-periodic in nature and potentially variable in amplitude. Commonly utilized frequency power spectrum techniques assume strict periodicity and symmetric profiles, and often report underestimated or completely indeterminate period errors. To address these issues, we are developing a quasi-periodic Gaussian Process (GP) fitting model combined with an MCMC sampling routine to determine parameter estimates and more reliable error bars (Rasmussen & Williams 2006; Ambikasaran et al. 2015; Vousden et al. 2016). Our version simultaneously fits for starspot cycles and rotational variability, as both are present in our data. The two center panels of Figure 4 illustrate two GP fits; in particular, the fit for GJ 1061 shows the complex nature of the light curve when long-term and rotational modulations are both present.

Ultimately, our data can be merged with other long-term datasets to enrich cycle coverage. ASAS-3 data span 2000-2009 (Pojmanski 2002), but offer incomplete coverage and/or poor precision ($\geq$ 50 mmag) for our red dwarfs, for which we routinely reach $\sim$7 mmag at the 0.9m. Despite this, ASAS-3 can sometimes uncover large amplitude cycles (e.g, Suárez Mascareño et al. 2016), and the next generation ASAS-SN has up to 5 years of data at $\geq$ 20 mmag precision (Jayasinghe et al. 2019) that may prove useful for some stars. Preliminary tests suggest that careful combinations of RECONS, ASAS-3, and ASAS-SN data (using filter offsets when necessary) can identify miscaptured trends and yield improved cycle coverage because of extended baselines. *Gaia* also provides suitable precision and cadence to potentially detect short-period cycles (Distefano & Lanzafame 2020). Merging *Gaia* with RECONS data could prove to be particularly valuable because the two data streams will overlap in time.[2]

5.4.2 Rotation

We will obtain rotation periods for our stars in order to accurately place them in appropriate dynamo regimes, and to construct the $log(P_{cyc}/P_{rot})$ vs. $log(1/P_{rot})$ diagram. Once determined, rotation periods can be modeled and long-term cycles can emerge more clearly. The 0.9m data are primarily used for the long-term cycles, but we can also use the 0.9m to acquire our own high-cadence rotation data — we have already secured additional time on the 0.9m via NOIRLab in addition to our SMARTS time to determine rotation periods for several dozen stars. Rotation periods can also be extracted from other available datasets taken on the ground and in space. Alas, *Kepler* observed in a different hemisphere than we do so is not useful for our stars, and *K2* did not observe many of our targets. In contrast, preliminary checks indicate that *TESS* data — when available and uncorrupted by nearby sources — will also be effective for determining rotation periods for cases shorter than its typical 27 day baselines. In addition, rotation periods for several hundred nearby red dwarfs are available via HATNet (Hartman et al. 2011), EvryFlare (Howard et al. 2020), CARMENES (Díez Alonso et al. 2019), APACHE (Giacobbe et al. 2020), *Gaia* DR2 (Lanzafame et al. 2018), and others. Particularly useful are the results for 662 red dwarfs from MEarth (Irwin et al. 2011; Newton et al. 2016, 2018), who are targeting many of the same red dwarfs in our SURVEY sample and with whom we have been collaborating — we have already found 120 stars in common.

Overall, our long-term datasets, the expertise developed via our new analysis methods, and baseline-extending data compilations will all put our group in a leading position to investigate potential links between stellar rotation and starspot cycles, and place us at the forefront of understanding the dynamos of red dwarfs.

5.4.3 Cycles and Rotation for Three Samples

SURVEY Stars (Couperus) — We are observing the 466 red dwarfs in the statistically representative set of SURVEY stars that span the entire M dwarf sequence (§5.1, Table 1, left panel of Figure 1). This is in stark contrast to all existing studies, which are opportunistic in reporting cycles and rotation where they have been detected, rather than pressing for statistical results. We observe stars in all of the aforementioned dynamo regimes: the Blue stars are partially radiative and the Green/Red subsamples are fully convective, which is the least studied population with the greatest promise of progress. With three more years of support, we will have datasets on 336 stars in the SURVEY sample lasting 6–25 years. We will characterize dozens of new red dwarf cycles and inform competing dynamo models, and make the first deep foray into the realm of cycles for fully convective stars. *For each subsample of SURVEY stars, we will provide statistics for cycle periods, amplitudes, and occurrence rates, link the results to rotation, and determine whether or not there are differences in the cycles of partially radiative versus fully convective red dwarfs.*

Stellar TWINS (Couperus) — We are observing 36 pairs of virtually identical stars in the TWINS sample (§5.1, right panel of Figure 1), constructed by searching *Gaia* DR2 for bound binaries that are (a) within 50 pc, (b) separated by 4–300″ to permit straightforward resolution of the components, (c) M dwarfs based on $BP - RP$ color and M_G, and (d) have *Gaia* BP, RP and 2MASS JHK_s photometry differing by less than 0.1 mag. Thus, components

[2] APASS is not suitable for this type of study because many of the targeted stars are only observed a few times, have typical errors of more than 50 mmag/epoch, or are not observed at all because they are too faint. Unfortunately, *Kepler* pointed only to the northern sky so did not observe our targets, nor did it reach past 4 years, and *K2* and *TESS* are not suitable for cycles due to their short-term observing windows.

are nearly identical from 0.5–2.2 μm, at which they emit most of their light, and have masses differing by $< 3\%$ in all cases (masses based on Benedict et al. 2016). Because these stellar twins are also presumably the same age and metallicity, evolutionary models and conventional thinking suggest that they might evolve similarly, resulting in comparable rotation rates, flare frequencies, coronal emission, spot activity, and long-term spot cycles.

However, a picture of highly complex and perhaps even non-deterministic magnetic evolution for red dwarfs is emerging. Examples include the proposed bi-stable dynamo in rapidly rotating late M dwarfs implying that similar stars can host wildly different magnetic structures (Morin et al. 2010; Gastine et al. 2013; Shulyak et al. 2017), sustained Hα activity differences between twin-like wide binary M dwarf components (Gunning et al. 2014), the clear bimodal distribution of rotation periods in M dwarfs (Newton et al. 2018), and the near-twin binary GJ 65AB that exhibits remarkably different activity levels and field topologies between the two components (Kochukhov & Lavail 2017; Barnes et al. 2017). Our TWINS sample goals are to (1) check for discordant rotation periods for twin stars, (2) reveal *any* indications of pairs with differing magnetic activity, (3) disclose whether or not activity depends on H-R diagram location relative to the border between partially radiative and fully convective stars (near $BP - RP = 2.5$ in Figure 1, right), and (4) present our sample of TWINS for related followup study (e.g, flaring activity, radio emission, Zeeman-Doppler imaging, etc). As fortune would have it, one of the 36 sets of TWINS has been on our program at the 0.9m since 2013, so we have an initial dataset to examine. Lightcurves for the two components of GJ 1183 shown in the upper right panel of Figure 4 are very different, with variability levels at V over 7 years of 24 mmag for A and only 9 mmag for B. This is curious, given that A is only 0.04–0.06 mag brighter than B from *Gaia BP* through 2MASS K_s. We are targeting the TWINS systems for long-term variability and rotation at the 0.9m, checking Hα activity at the CTIO/SMARTS 1.5m (where we have preferred access), and have *Chandra* x-ray observations scheduled for 4 pairs. *For the 36 TWINS pairs, we will test how well their rotation, activity levels, and magnetic characters match, and provide excellent test cases for dynamo theory.*

Nearby Red Dwarfs with Exoplanets (Kar) — We are observing 45 (so far) of the nearest red dwarfs within 25 pc reported to have exoplanets. This is a new project for the RECONS team, although we have a significant amount of data in-hand because we have been observing some stars for a decade or more that have now been reported to have planets. This effort can be considered a subset of the larger variability project, and a new graduate student, Aman Kar, joined the RECONS group in Fall 2020 and has quickly invested in this science.

We start with the long-term datasets we have already secured at the 0.9m. As shown in the lower right panel of Figure 4, results for the first 22 stars with at least 6 years of data indicate that 19 (86%) exhibit variability levels of ≤ 20 mmag (2%) in the optical VRI bands, where these stars emit most of their flux. Thus, the initial results bode well for stable planetary environments around most red dwarfs. Notable exceptions are Proxima Centauri (1 or 2 planets), GJ 1061 (3 planets, with a complicated light curve shown in the lower middle panel Figure 4), and GJ 876 (4 planets). Among the SURVEY list of 466 red dwarfs, additional planets will undoubtedly be found for stars for which we already have long-term coverage — we just don't know *which* ones have planets. We expect that in the next few years the available sample is likely to double, given recent announcements like that for GJ 1061 (Dreizler et al. 2020). While the first glance implies that most red dwarfs provide stable flux enviroments for orbiting planets at optical wavelengths, we will expand our studies to x-ray and ultraviolet wavelengths, where stellar variability can have particularly adverse affects on planetary atmospheres. *For the exoplanet host stars, we will carry out a systematic reconnaissance to evaluate the sorts of environments experienced by many of the nearest exoplanets.*