New Rotation Period Measurements for M Dwarfs in the Southern Hemisphere: An Abundance of Slowly Rotating, Fully Convective Stars

Elisabeth R. Newton1,4, Nicholas Mondrik2,3,5, Jonathan Irwin3, Jennifer G. Winters3, and David Charbonneau3

1 Massachusetts Institute of Technology Kavli Institute for Astrophysics and Space Research, 77 Massachusetts Avenue, Cambridge, MA 02139, USA
2 Department of Physics, Harvard University, 17 Oxford Street, Cambridge, MA 02138, USA
3 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Received 2018 May 18; revised 2018 June 29; accepted 2018 July 5; published 2018 October 18

Abstract

Stellar rotation periods are valuable both for constraining models of angular momentum loss and for understanding how magnetic features impact inferences of exoplanet parameters. Building on our previous work in the northern hemisphere, we have used long-term, ground-based photometric monitoring from the MEnthor Observatory to measure 234 rotation periods for nearby, southern hemisphere M dwarfs. Notable examples include the exoplanet hosts GJ 1132, LHS 1140, and Proxima Centauri. We find excellent agreement between our data and K2 photometry for the overlapping subset. Among the sample of stars with the highest quality data sets, we recover periods in 66%; as the length of the data set increases, our recovery rate approaches 100%. The longest rotation periods we detect are around 140 days, which we suggest represent the periods that are reached when M dwarfs are as old as the local thick disk (about 9 Gyr).

Key words: stars: individual (Proxima Centauri, Wolf 359, GJ 1286) – stars: low-mass – stars: rotation

Supporting material: machine-readable table, figure set

1. Introduction

1.1. Measuring Rotation Periods to Inform Studies of Angular Momentum Evolution

Stars are born with rotation periods between 1 and 10 days, and experience initial spin-up as they contract onto the main sequence. Stars with masses below the Kraft break (Schatzman 1962; Kraft 1967), that is, which have convective envelopes, subsequently lose angular momentum through the coupling of the stellar wind to the magnetic field. The distribution of rotation periods has been well explored for solar-type stars from both an observational and a theoretical perspective (see Bouvier et al. 2013, for a review). Results from clusters at ages up to 4 Gyr (Barnes et al. 2016) indicate agreement between the observed stellar rotation periods and previously developed rotation-age (“gyrochronology”; Barnes 2003) relations.

Long-lived M dwarfs provide the opportunity to test the angular momentum evolution models that are traditionally tuned to the Sun. Models parameterize the way in which the magnetic field and mass loss produce a torque, which acts to remove angular momentum from the star; the magnetic field strength and topology and the mass-loss rate are thought to depend on the star’s mass and rotation rate. These models are fit to the ages and rotation rates of groups of stars, with most models to-date having focused on partially convective stars similar to the Sun. Several works have recently assessed models for both partially and fully convective stars, but there remain challenges in fitting both groups and, in particular, the slowly rotating fully convective stars (e.g., Reiners & Mohanty 2012; Matt et al. 2015; Douglas et al. 2016).

The lowest mass M dwarfs are additionally challenging for theoretical models because much of their angular momentum evolution takes places at ages older than the oldest clusters in which such stars are accessible. M dwarfs in the field of the galaxy therefore provide important probes of spindown. Photometric surveys over the past 10 years, many of which have been motivated by the search for exoplanet transits, have yielded a plethora of rotation periods for field M dwarfs. Significant samples of rotating field M dwarfs have been contributed by HAT-Net (Hartman et al. 2011), MEarth (Irwin et al. 2011; Newton et al. 2016a), Pan-STARRS (Kado-Fong et al. 2016), and Kepler (McQuillan et al. 2013). These studies of field stars complement those undertaken for clusters from the ground (e.g., Irwin et al. 2007; Hartman et al. 2010; Covey et al. 2016) and from space (e.g., Rebull et al. 2016; Douglas et al. 2017).

Mid-to-late M dwarfs (0.08 < M* < 0.3 M☉) have not generally been accessible in wide-field surveys due to their intrinsic faintness. Thus, in order to connect the rotational evolution of these very low-mass stars to F, G, K, and early M dwarfs, we must independently seek out their rotation periods.

1.2. The Importance of Rotation Periods to Exoplanet Research

Not only are the rotation periods of field stars critical for stellar physics, but they are also important for enabling exoplanet research. Stellar rotation imprints itself on both photometry and radial velocity data, and thus the detection and characterization of planets near the stellar rotation period or its low-order harmonics can be frustrated. For early M dwarfs, the typical rotation periods for older field stars coincides with orbital periods of planets in the habitable zone (Newton et al. 2016b; Vanderburg et al. 2016). This can inhibit the detection of potentially habitable planets around these stars (e.g., Gl 581; Robertson et al. 2014) or the determination of masses for temperate planets discovered via their transits (e.g., K2-3; Almenara et al. 2015; Damasso et al. 2018).

The Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2014) launched in 2018 April with the goals of finding small planets around bright, nearby stars and measuring the masses for 50 planets with radii <4R⊕. TESS’s observing
window ranges from 27 days near the ecliptic to one year at the ecliptic poles, with one year spent in each of the ecliptic hemispheres over the course of its nominal two-year mission.

*TESS*’s time baseline combined with its small aperture means that the habitable-zone planets to which *TESS* will be sensitive are those that orbit M dwarfs (see Figure 21 in Sullivan et al. 2015). Though it will be possible to identify some periods from the *TESS* data alone, the typically short time baseline will inhibit the detection of the long rotation periods common among M dwarfs. Thus, ancillary data will be needed to make the best use of limited resources for follow-up. Obtaining an optical spectrum to measure stellar magnetic activity provides one easily accessible avenue. For example Astudillo-Defru et al. (2017) calibrated period as a function of Ca H and K emission strength. In Newton et al. (2017) we noted that if an M dwarf is inactive at Hα it definitively identifies it as a slow rotator and presented a mass-period relation for Hα-inactive M dwarfs.

Measuring the photometric behavior of a particular planet-host of interest is important for constraining the impact of spots on transit properties, and for modeling magnetic activity signatures in radial velocity measurements. Slowly rotating, inactive M dwarfs may represent more hospitable environments for life. This is because high-energy radiation and stellar mass loss can result in extensive atmospheric erosion for temperate planets around active M dwarfs (e.g., Lammer et al. 2007; Luger & Barnes 2015; Garraffo et al. 2017; Cohen et al. 2018). Slowly rotating M dwarfs are likely to have fewer flares and CMEs, weaker stellar winds, and lower levels of X-ray and UV emission. Ultimately, it may also be possible to use the rotation period of an M dwarf to determine its age via gyrochronology (Barnes 2003).

### 1.3. This Work

The photospheres of distant stars are thought to be blemished by persistent magnetic features akin to the spots seen on the Sun. The presence of spots modulates the stellar brightness as they rotate in to and out of view; measuring the periodicity of brightness variations therefore allows one to infer the rotation period of the star. The result is typically referred to as a photometric rotation period, which contrasts with periods inferred from velocity broadening of spectral lines ($v \sin i$).

Our work in Newton et al. (2016a) provides the majority of photometric rotation period measurements for field M dwarfs below the fully convective boundary. These 387 rotation period measurements are based on photometry from the MEarth Project, using data obtained with the project’s northern observatory, MEarth-North, located at the Fred Lawrence Whipple Observatory, on Mount Hopkins, Arizona. In this paper, we extend our analysis to the southern sky using data from MEarth-South. As for our northern search, our current work benefits from our survey’s multiyear time baseline and consistent observing setup. *TESS* will begin its survey in the southern ecliptic hemisphere, which overlaps substantially with our survey area; due to their proximity to Earth, many of the nearby southern M dwarfs that are the subject of this work will be prime targets during *TESS*’s first year for the detection of small planets and characterization of their masses and atmospheres.

### 2. Our Southern M Dwarf Sample

#### 2.1. The MEarth Project

The MEarth Project is an all-sky survey of approximately 3000 nearby, predominantly mid-to-late M dwarfs (Berta et al. 2012; Irwin et al. 2015). The survey’s second site, MEarth-South, was commissioned in 2014 January. The survey design, data analysis, and period detection for MEarth-South are similar to those for MEarth-North. We provide an overview and point out differences here, but refer to Irwin et al. (2015) and Newton et al. (2016a) for details.

Like MEarth-North, MEarth-South comprises eight 40 cm telescopes on German Equatorial Mounts, equipped with CCD cameras. These telescopes are housed in a roll-off roof at Cerro Tololo Inter-American Observatory (CTIO) in Chile. Exposure times are set independently for each star based on the S/N required to detect small planets. We use a maximum exposure time of 75 s, so this S/N is achieved by coadding individual exposures. Multiple exposures are also obtained for bright targets in order to average over scintillation noise. We term one set of coadded exposures a *visit*. There are typically between 1 and 25 visits per night, per target.

The MEarth-South survey is ongoing; the analysis presented here uses data obtained prior to BJD 2458179.5 (12am 2018 March 2 UT). We analyze data from 574 stars from MEarth-South. Data from MEarth-North are not analyzed, except in Section 3.3 for stars that overlap with K2.

#### 2.2. Stellar Parameters

Trigonometric, photometric, and spectroscopic information were collected from the literature for stars in the MEarth target list. Table 1 includes parallax, proper motion, radial velocity, and rotation period measurements, as well as several derived parameters. Parallaxes are not used when the measurement was less than three times the error in the measurement. When parallaxes are not available, we used photometric relations from Henry et al. (2004) to estimate distances; if optical ($V, R_c, I_c$) photometry is not available, estimates are taken from Lépine (2005).

We used 2MASS $K$ magnitudes to infer stellar masses and applied the the mass–radius relation from Boyajian et al. (2012) to estimate stellar radii. There are two commonly used relations to infer mass from $K$ magnitude: Benedict et al. (2016) and Delfosse et al. (2000). The two calibrations agree within 0.01 $M_\odot$ for M dwarfs with masses from 0.09 to 0.22 $M_\odot$, but the disagreement is worse at higher stellar masses. The results presented in this paper use Delfosse et al. (2000), extrapolated as described in Newton et al. (2016a). This is for consistency with our previous work and because a mass–radius calibration has not been published for use with Benedict et al. (2016).

#### 2.3. MEarth-South Target List

The targets for MEarth-North were selected from the Lépine & Shara (2005) northern proper motion catalog using distance (Lépine 2005), radius, and color cuts (Nutzman & Charbonneau 2008). For MEarth-South (Irwin et al. 2015), we began with nearby M dwarfs with measured trigonometric parallaxes from the Research Consortium on Nearby Stars (RECONS) published in Winters et al. (2015) and spectroscopic characterization from

---

6 http://www.recons.org/publishedpi.2012.1016
the Palomar/Michigan State University (PMSU) spectroscopic survey (Reid et al. 1995; Hawley et al. 1996). We then added stars from the LSPM-South catalog (S. Lépine 2018, private communication), from which we used color and reduced proper motion cuts from Lépine & Gaidos (2011) to select nearby M dwarfs.

We then vetted stars to remove known close binaries prior to their inclusion in our southern target list. Rapidly rotating stars and close binaries are continuously removed from the active target list as they are identified. Stars are also typically removed from observation when they have increased radial velocities. Due to the provenance of the southern radial velocities, the southern stars with all three components of motion measured are biased toward kinematically older stars.

We initially search periods between 0.1 and 1000 days, but for stars with candidate periods <0.2 days, we repeated the search allowing periods as short as 0.05 days. A typical occurrence is that long-term, nonrepeating variability will manifest as either a 1 day period or a very long (500–1000 day) period. We try searching narrower period ranges for literature are from the PMSU Survey conducted in the 1990s, which targeted high proper motion stars included in the 3rd edition of the Catalog of Nearby Stars (CNS3; Gliese & Jahreiß 1991). The CNS3 proper motion limits are higher than the limits of present-day proper motion surveys. Therefore, the southern stars with radial velocities are biased toward those with high proper motions. This effect is not seen in the north because numerous surveys have targeted northern M dwarfs, basing their target lists on more recent catalogs.

### 3. Rotation Period Measurements

#### 3.1. Period Fitting Algorithm

To detect rotation periods, we use the “least squares periodogram” method as described in Irwin et al. (2006). The application to MEarth data is described in Irwin et al. (2011) and Newton et al. (2016a). We simultaneously fit for systematics and a sinusoid. Our systematics includes magnitude offsets corresponding to the changes in our detectors and for observations obtained on each side of the meridian, and the "common mode." The common mode derives from variations in precipitable water vapor, which differentially affects our late-type science targets and our earlier-type comparison stars; as will be discussed later, this impacts our ability to detect rotation periods. The sinusoid we presume to be the result of starspots rotating in and out of view.

All parameters except the period are fit using linear least squares. We step through a grid of rotation periods and record the F-test goodness of fit metric at each period, the result of which is a periodogram where the power is given by the F-test statistic. The candidate period is the one with the highest F-test statistic.

We initially search periods between 0.1 and 1000 days, but also explore parameter space manually using a custom GUI. For stars with candidate periods <0.2 days, we repeated the search allowing periods as short as 0.05 days. A typical occurrence is that long-term, nonrepeating variability will manifest as either a 1 day period or a very long (500–1000 day) period. We try searching narrower period ranges for
though comparison between our measurements and literature results suggests that we have identified the correct period for many candidate rotators, we limit our analysis to grade A and B rotators. We present our periods in Table 1; ratings are indicated in the first column by a letter. We do not report periods for nondetections, and note that periods for nondetections listed in Newton et al. (2016a) should not be used.

Table 1 contains periods for stars whose apertures are severely contaminated by a physically associated or background companion. These objects are flagged in the table but are not included in the analysis that follows.

### 3.3. Comparison with K2

**Kepler** observed some stars in our sample as part of the K2 ecliptic survey. We identified M dwarfs in the MEarth data set that had also been observed by K2. Several of these stars are part of the MEarth-North data set and not in the sample of stars otherwise included in this work; these stars are analyzed in this section only. We downloaded the K2 light curves available on MAST as of 2018 January 17. We considered every data reduction available on MAST but found that the K2SSF (Vanderburg & Johnson 2014) and the PDC-MAP (Smith et al. 2012; Stumpe et al. 2012) reductions best served our purposes. We use the **astropy** (The Astropy Collaboration et al. 2013) package to compute a Lomb Scargle periodogram and our custom visualization tool to examine each light curve by eye (see footnote 7).

---

**Table 2**  
Stars in Our Sample Also in K2

| 2MASS ID     | EPIC ID     | $P_1$ (K2) | $P_2$ (K2) | Source$^b$ | $P$ (MEarth) | Rating | $N_{det}$ |
|--------------|-------------|------------|------------|------------|-------------|--------|----------|
| 10252465+0512391 | 248574998   | 0.09254    | ...        | k2sff      | 0.09253     | A      | 1124     |
| 10562866+0700527 | 201885041   | 2.713      | ...        | ktwo       | ...         | N      | 2774     |
| 11280702+0141304 | 201577109   | 0.1687     | 0.1369     | ktwo       | 0.1687      | A      | 1029     |
| 12115719+0720136 | 228786554   | ...        | ...        | k2sff      | 140.5       | B      | 3796     |
| 12220398+0629123 | 228807026   | 1.24       | ...        | k2sff-c102 | 1.24        | U      | 681      |
| 12235208+0858432 | 228748748   | 0.471      | ...        | k2sff      | ...         | N      | 9        |
| 12384731+0419168 | 228858734   | ...        | ...        | ktwo       | ...         | N      | 1620     |
| 13215411+1424098 | 212422696   | 1.296      | ...        | ktwo       | ...         | N      | 26       |
| 13300285+0842251 | 212681564   | ...        | ...        | k2sff      | ...         | N      | 917      |
| 13515712+1758490 | 212285198   | ...        | ...        | k2sff      | ...         | N      | 29       |
| 16131715+2538139 | 205858533   | ...        | ...        | k2sff      | ...         | N      | 350      |
| 16204186+2005139 | 204957517   | 2.82       | 2.106      | k2sff      | 2.814       | B      | 1212     |
| 16352464+2718533 | 203087352   | ...        | ...        | k2sff      | 122.7       | A      | 3815     |
| 16563362+2046373 | 2040806561  | 0.5724     | ...        | k2sff-c111 | 0.5711      | A      | 1980     |
| 18471674+1922202 | 218121888   | ...        | ...        | k2sff      | 152.1       | B      | 1893     |
| 18494929+2350101 | 215632123   | 2.857      | ...        | ktwo       | 2.843       | A      | 1428     |
| 19042185+2406457 | 215493021   | ...        | ...        | ktwo       | ...         | N      | 620      |
| 19163233+2322224 | 215875814   | ...        | ...        | ktwo       | ...         | N      | 2265     |
| 22134277+1741081 | 205913009   | ...        | ...        | k2sff      | ...         | N      | 4194     |
| 22260112+1518128 | 205983882   | 0.2288     | ...        | ktwo       | ...         | N      | 22       |
| 22285440+1325178 | 206050032   | ...        | ...        | ktwo       | ...         | N      | 4680     |
| 22341112+1020135 | 206169145   | 0.4834     | ...        | ktwo       | ...         | N      | 102      |
| 23172072+0236323 | 246322698   | 0.341      | ...        | ktwo       | 0.341       | B      | 1581     |
| 23180785+0234475 | 246324216   | ...        | ...        | k2sff      | 114.5       | U      | 1581     |
| 23351050+0232214 | 246333864   | ...        | ...        | k2sff      | 88.92       | A      | 3624     |
| 23552591+0359000 | 246253313   | ...        | ...        | k2sff      | 54.47       | A      | 2584     |

Notes.  
$^a$ Secondary peak in the periodogram when clearly present.  
$^b$ Source of K2 indicated using the MAST prefix of the datafile used. “k2sff” is from Vanderburg & Johnson (2014) and “ktwo” is the PDC-MAP reduction. For Campaigns 10 and 11, the PDC-MAP data is split into two light curves and we have indicated the segment used.
We find clear rotation periods for 12 stars from K2, all of which are less than three days. Of these, seven have rotation periods from MEarth, all of which are in agreement. For 2MASS J11280702 +0141304/EPIC 201577109 and 16204186−2005139/EPIC 204957517, the K2 light curves indicate two distinct rotation periods. This suggests that the targets may be blended, but could also indicate differential rotation. We present a comparison between the MEarth and K2 rotation periods in Table 2 and in Figure 2.

Five stars have rotation periods from K2 but not from our work with MEarth. For four of these, we have <100 observations with MEarth and we do not expect to detect rotation with such limited data. The fifth star is Wolf 359 (2MASS J10562886+0700527, EPIC 201885041), an M6 dwarf (Kirkpatrick et al. 1991) for which the K2 data clearly indicate a 2.7 rotation period.8 This object suffers from unfavorable observing conditions (see also Section 4.3).

For the stars for which we have identified long rotation periods, we do not expect to detect rotation periods in the K2 data given the short length of the K2 campaigns, and indeed we find no periods for these long rotators. We jointly examine the MEarth and K2 light curves for each M dwarf with a confirmed or candidate rotation period from MEarth. Though the available data reductions do not aim to preserve stellar variability on the timescale of a K2 campaign, we find that the long-term modulations present in the K2SFF reduction are roughly consistent with what we would expect given the rotation period from MEarth.

This is particularly striking for GJ 1286 (2MASS 23351050−0223214, EPIC 246333864), for which we detect rotational modulation at 89 days. GJ 1286 is an M5.5 dwarf (Henry et al. 1994) at 7.2 pc (Weinberger et al. 2016). K2 Campaign 12 observations commenced as GJ 1286 set for our Earth-bound observatories. Comparing the MEarth and K2SFF light curves, it is clear that the two data sets are consistent, both showing near-sinusoidal modulation (Figure 3).

4. Results

4.1. Stars with Detected Rotation Periods

Figure 4 shows an overview of the rotation periods detected in this work. We detected 234 rotation periods after having searched 574 stars, which comprises 142 grade A rotators and 92 grade B rotators. We also find 47 candidates. Phase-folded light curves are shown in Figure 5. As in Newton et al. (2016a), we use the results from Irwin et al. (2011) to estimate that our errors in rotation period are about 10%. The periods and amplitudes show patterns consistent with those presented in Newton et al. (2016a), including the dearth of stars with intermediate rotation periods (approximately 10–70 days). We also find no intermediate rotators among the nearby M dwarfs observed by K2.

We note that aliases are likely present, and in some cases it is challenging to distinguish the two most likely possibilities. For example, in 2MASS J06464109−2150161 and 2MASS J17281105−0143569, periods of around 1 day and around 30 days both provide reasonable fits to the data, and the precision and quantity of data over a single night is not sufficient to distinguish the two. Higher cadence monitoring would be beneficial.

As in Newton et al. (2016a), sinusoidal patterns dominate the light curves of stars with detected rotation periods. However, aided by the lack of a monsoon season imposing summer-long gaps in, and the generally higher S/N of our southern data, we see clear departures from sinusoids in a number of cases. This could affect our best-fitting rotation periods, which we suggest on the basis of our 89 day period for Proxima, in contrast to the 83 day period consistently reported in the literature (Benedict et al. 1998; Wargelin et al. 2017). Using Gaussian processes to model the stellar variability (e.g., Cloutier et al. 2016; Angus et al. 2018) for cases of unique interest would likely be beneficial.

Among the stars in our sample is the mid M dwarf Proxima Centauri, the nearest star to us. Benedict et al. (1998) reported an 83 day rotation period for Proxima using the Hubble Space Telescope Fine Guidance Sensors, which was confirmed by Kiraga & Stepień (2007, 82.5 days) and others. Recently, Wargelin et al. (2017) identified a 7 year activity cycle for Proxima based on a 15 years of photometry from ASAS (Pojmanski 2002). Our light curve of Proxima is shown in Figure 6. We measure a rotation period of 89 days.

Our sample also includes the planet hosts GJ 1132 (Berta-Thompson et al. 2015) and LHS 1140 (Dittmann et al. 2017). Rotation periods for both of these stars, measured from MEarth-South data, were presented in those works. They are 125 days for GJ 1132 and 131 days for LHS 1140. For GJ 1132, Cloutier et al. (2016) measure 122±5 days using Gaussian process modeling applied to the MEarth data then available (the first half of the current data set, through BJD 2457285). The period we calculate based on the current data set is 130 days for GJ 1132, within the approximately 10% error bars. LHS 1140’s period is unchanged. The light curve of GJ 1132 is shown in Figure 7, and demonstrates substantial spot evolution on timescales similar to the rotation period.

4.2. Period Recovery Rates

We separate the data into evenly spaced bins based on the length of the data set and calculate the recovery rate in each bin, shown in Figure 8. If stars were observed with both MEarth-North
and MEarth-South, they are categorized as being part of the southern sample. We consider only stars with radii between 0.15 and 0.33 $R_\odot$. The upper limit is set by the fiducial radius limit for MEarth; the lower limit is a result of our decreasing sensitivity to rotation periods at lower masses due to precipitable water vapor variations (discussed in the following section). We assume that period detections represent independent binomial trials, and use the statsmodel package (Seabold & Perktold 2010) to calculate confidence limits for a binomial proportion. The error bars in Figure 8 represent the 68% confidence interval.

We find a striking positive correlation between the length of the data set and the fraction of stars in which periods are detected, with the recovery rate reaching 80% for data sets with observations on $\gtrsim 350$ separate nights (bottom panel). In Newton et al. (2016a), our overall recovery rate in the subset of northern stars termed the “statistical sample” was $47 \pm 3\%$. The statistical sample was defined as all stars with $>1200$ visits in a single light curve and median error per visit $<0.005$ mag. Considering the same constraints in the south, our recovery rate is $66 \pm 3\%$.

In the following section, we will consider stars for which the median error in one visit is $<0.005$ mag and for which observations were acquired on $\gtrsim 350$ individual nights (having 350 days of observations generally involves an observing baseline of around 1000 days, given weather and seasonal observing gaps). We found that this better represented our by-eye assessments of whether a rotation period had been detected than the $>1200$ visit requirement. We note that we regularly drop stars from the survey when they reach this limit; this choice was set by sensitivity to planets, but we coincidentally find that 350 days is a reasonable cutoff for rotation period monitoring. In this subset of stars, our recovery rate is $79 \pm 5\%$.

4.3. Stars without Detected Periods

For stars with $<350$ nights of observations or typical errors $\gtrsim 0.005$ mag, the most likely cause of a nondetection is an insufficient amount or quality of data. There persists a small number of stars for which we have gathered thousands of data points but for which a period detection has not resulted; there are 78 stars for which the median error in one visit is $<0.005$ mag and for which observations were acquired on $\gtrsim 350$ individual nights. Of these, we detect periods in 62. As in previous parts of this paper, we are not considering stars that are close binaries or that are strongly overluminous.

---

9 The error bar here, calculated as the 68% confidence interval on the binomial proportion, and differs from that in Newton et al. (2016a).
The light curves for the remaining 16 stars with high quality data sets and without period detections are shown in Figure 9. We did not identify a single unifying feature that determined whether or not we would detect a rotation period for a star that otherwise had sufficient length and precision. The nondetections likely comprise several different categories: (1) stars with unfavorable observing conditions, (2) later-type stars, (3) long rotators with evolving spot patterns or low spot contrasts. We discuss these further below.

(1) Some stars are not favorably situated for observing with MEarth. This includes stars that have companions that are resolved, but close enough to contaminate the aperture in poor conditions. Periods close to 1 day are also challenging to disentangle from systematics. Our noise model includes scintillation noise and scatter in comparison stars; stars so impacted would generally be excluded by the precision cut, but these factors could contribute to systematic errors.

The light curves for the remaining 16 stars with high quality data sets and without period detections are shown in Figure 9. We did not identify a single unifying feature that determined whether or not we would detect a rotation period for a star that otherwise had sufficient length and precision. The nondetections likely comprise several different categories: (1) stars with unfavorable observing conditions, (2) later-type stars, (3) long rotators with evolving spot patterns or low spot contrasts. We discuss these further below.

(1) Some stars are not favorably situated for observing with MEarth. This includes stars that have companions that are resolved, but close enough to contaminate the aperture in poor conditions. Periods close to 1 day are also challenging to disentangle from systematics. Our noise model includes scintillation noise and scatter in comparison stars; stars so impacted would generally be excluded by the precision cut, but these factors could contribute to systematic errors.

The Astronomical Journal, 156:217 (11pp), 2018 November Newton et al.
Nondetections are biased toward later-type stars, with a drop-off in our recovery rate for $M_* < 0.2 \, M_\odot$. The mass of all stars with and without detections are significantly different; the $p$-value of an Anderson–Darling test is $p = 0.006^{+0.014}_{-0.005}$. For the restricted subset of targets considered in this section, 81% of nondetections, and 60% of detections have $M_* < 0.2 \, M_\odot$; the difference in mass distributions is not significant, but the number of stars in the samples is insufficient for the effect to be reliably seen. The bias is likely due to our diminishing ability to correct for systematics for redder stars: lower mass stars are more greatly impacted by precipitable water vapor variations, which can in particular inhibit the detection of short periods. 

Most nondetections show some sort of variability, and for seven we have identified candidate long periods with periods typical of our detections. However, the photometric variability is not observed to repeat or is very low amplitude. With extended monitoring, we might happen upon an epoch in which the spot pattern is more stable or in which the contrast between spotted and unspotted photosphere is greater, and would detect a rotation period.

A final possibility is that stars are inclined such that their poles point directly ($0^\circ$) or near-directly at us; these stars would show no variability or much reduced amplitudes than if they were to be viewed edge-on. How important an effect this is depends on how spots are distributed on the stellar surface. Rebull et al. (2016) identified rotation periods in 92% of stars in the Pleiades using K2, and remark that the remaining 8% present unfavorable conditions (e.g., are too bright). Thus, this is not likely an important effect for rapidly rotating stars. The spot distribution of slow rotators has not been studied in as much depth.

Considering our search for long rotation periods, (3) is the most relevant. Our hypothesis is that the nondetections shown in Figure 9 are drawn from the same population as the detections. In support of this, we detect candidate periods of similar length to our rotators for seven of these stars, but the variability is intermittent or quasi-periodic, and sometimes low amplitude. We suggest that the nondetections reflect the unfavorable end of the distribution of spot lifetimes, having $\tau_{\text{spot}} \leq P_{\text{rot}}$. Alternatively, this group could represent stars with a fundamentally different type of spot or dynamo behavior.

5. Summary and Discussion

We use long-term photometric monitoring from MEarth-South to measure the rotation periods of 234 M dwarfs in the...
Figure 7. We show the southern sample recovery rate is the fraction of surveyed stars for which a period was detected, southern hemisphere. Our rotation period search benefited from the long time baseline and high cadence of our data set, and consistent observing strategy. We note that we find it challenging to disentangle daily aliases in some cases; continuous monitoring from TESS will settle the uncertainties.

We see substantial spot evolution in some stars (see Figure 7). Different modeling techniques, such as Gaussian processes (e.g., Angus et al. 2018) would be beneficial in these cases. Spot evolution is also important for planning exoplanet observations: as a consequence of changing surface patterns, it is optimal to have long-term photometric monitoring that coincides with transit and radial velocity measurements if we are to constrain the impact of spots and magnetic activity on these data (e.g., Pont et al. 2013; Mallonn et al. 2018; Rackham et al. 2018).

The fraction of stars in which we detect a rotation period increases steadily with increasing length of the data set. For the subset of stars with >1200 visits and median error <0.005 mag, the recovery rate is 67 ± 3%; for comparison it was 47 ± 3% for northern stars subject to the same selection criteria. Considering stars observed on ≥350 nights and with median error <0.005 mag, we recover periods in 62 of 78 stars, and candidate periods for 7. The spot patterns of many of these stars with detected periods seem stable for as long or longer than one rotation period ($\tau_{\text{spot}} \gtrsim P_{\text{rot}}$). We suggest that the nondetections are stars for which spot evolution timescales are similar to or shorter than the stellar rotation period ($\tau_{\text{spot}} \lesssim P_{\text{rot}}$), representing the unfavorable end of the distributions seen for long-period rotators. We do not think that there remains an unexplored population of rotators in our data.

As a consequence, we hypothesize that we are probing the longest rotation periods typically reached by Solar Neighborhood M dwarfs; these longest periods are around 140 days. The age of the local thick disk has been estimated to be 8.7 ± 0.1 Gyr by Kilic et al. (2017) using white dwarfs within 40 pc (which they note is younger than the canonical thick disk age at larger distances due to the dynamical evolution of stars in the galaxy). The period upper limit we see could reasonably be set by a combination of this finite age in combination with Skumanich-like angular momentum loss rates (see e.g., Irwin et al. 2011).

From an observational perspective, the Large Synoptic Survey Telescope (LSST; see Hawley et al. 2016) will provide the opportunity to probe the late-stage angular momentum evolution of M dwarfs through its precise, extensive, and long-term monitoring of M dwarfs. Though it is not expected to survey M dwarfs in clusters with ages >5 Gyr (the limit is younger for later-type M dwarfs), its sensitivity means that more distant and therefore sometimes older stars will be observed. If the period distribution we have detected so far results from the age of the local thick disk and M dwarfs continue to slowly spindown at ages beyond this, we should see M dwarfs with >140 day rotation periods with LSST.

The authors would like to acknowledge D. Kipping for encouragement in adding Proxima Centauri back into the sample after it was initially removed for being too bright. E.R.N. is supported by an NSF Astronomy and Astrophysics Postdoctoral Fellowship under award AST-1602597 and thanks DMC-Boston for the use of a spare desk and the snack cabinet. N.M. is supported by the National Science Foundation Graduate Research Fellowship Program, under NSF grant number DGE-1745303. N.M. thanks the LSSTC Data Science Fellowship Program; his time as a Fellow has greatly benefited this work. The MEarth project acknowledges funding from the National Science Foundation under grants AST-1616624, AST-0807690, AST-1109468, and AST-1004488 (Alan T. Waterman Award) and the David and Lucile Packard Foundation Fellowship for Science and Engineering. MEarth observations of GJ 1132 and LHS 1140 were supported in part through HST GO programs 14757, 14758, and 14888 which were provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. This publication was made possible through the support of a grant from the John Templeton Foundation. The opinions expressed here are those of the authors and do not necessarily reflect the views of the John Templeton Foundation.
Figure 9. Light curves for stars with $\geq$350 days of observations and median error per visit < 0.005 mag but without a rotation period detection (both candidate detections and nondetections are shown). The 2MASS ID and the candidate period (if identified) are shown at the top of each panel.

Foundation. This research has made use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by NASA and the NSF; NASA Astrophysics Data System (ADS); and the SIMBAD database and VizieR catalog access tool, at CDS, Strasbourg, France.
