A CATALOG OF ROTATION AND ACTIVITY IN EARLY-M STARS

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ABSTRACT

We present a catalog of rotation and chromospheric activity in a sample of 334 M dwarfs of spectral types M0–M4.5 populating the parameter space around the boundary to full convection. We obtain high-resolution optical spectra for 206 targets and determine projected rotational velocity, \(v \sin i\), and Hα emission. The data are combined with measurements of \(v \sin i\) in field stars of the same spectral type from the literature. Our sample adds 157 new rotation measurements to the existing literature and almost doubles the sample of available \(v \sin i\). The final sample provides a statistically meaningful picture of rotation and activity at the transition to full convection in the solar neighborhood. We confirm a steep rise in the fraction of active stars at the transition to full convection known from earlier work. In addition, we see a clear rise in rotational velocity in the same stars. In very few stars, no chromospheric activity but a detection of rotational broadening is reported. We argue that all of them are probably spurious detections; we conclude that in our sample all significantly rotating stars are active, and all active stars are significantly rotating. The rotation–activity relation is valid in partially and in fully convective stars. Thus, we do not observe any evidence for a transition from a rotationally dominated dynamo in partially convective stars to a rotation-independent turbulent dynamo in fully convective stars; turbulent dynamos in fully convective stars of spectral types around M4 are still driven by rotation. Finally, we compare projected rotational velocities of 33 stars to rotational periods derived from photometry in the literature and determine inclinations for a few of them.

Key words: stars: activity – stars: low-mass – stars: rotation

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1. INTRODUCTION

M dwarfs constitute the majority of stars in the solar neighborhood. They are intrinsically faint because they are cooler and smaller than all other stars, and their physical properties span more than a factor of five in mass and radius from the coolest late-M-type stars and young brown dwarfs with less than a tenth of a solar mass to the most massive M dwarfs with more than half a solar mass. Because of their faintness, detailed spectroscopic investigation is more observationally demanding than the analysis of brighter objects, but the sheer number of M stars renders them an excellent statistical sample for understanding properties of stellar physics and evolution. Many M dwarfs show substantial magnetic activity resulting in chromospheric and coronal heating, observed in various indicators across the whole stellar spectrum. It is often argued that M dwarfs are places of violent energy outbursts unsuitable for the existence of life. However, a large fraction of M dwarfs show little signs of magnetic activity, and M dwarfs have become a prime target for the search for Earth-like extrasolar planets.

The spectral type regime of early- to mid-type main-sequence M stars coincides with the mass regime where the transition from partial convection to full convection occurs (Chabrier & Baraffe 1997). Partially convective stars, or solar-type stars, are believed to generate at least parts of their magnetic fields through a global dynamo residing at the interface between the radiative core and the convective envelope. Rotational shear at this interface can amplify magnetic fields and sustain a cyclic magnetic dynamo (Parker 1993; Ossendrijver 2003). Field lines end up rising to the surface of the star and become visible in the form of starspots. Rotation, therefore, is the main driving force behind chromospheric and coronal activity. However, at \(M \sim 0.35 M_\odot\), stars are believed to become fully convective and no interface layer exists anymore in their interior. The stars also suffer significant structural changes leading to dramatic differences in mass and radius while effective temperature (spectral type) only changes little. Therefore, radius and mass are strongly related to spectral subtype around the boundary to complete convection, which can explain the observed change in braking efficiency and activity lifetimes in this mass regime (Reiners & Mohanty 2012).

Despite the changes in stellar structure, strong magnetic activity also appears in very low mass stars that are fully convective (Hawley et al. 1996; West et al. 2004). Observations of magnetically sensitive molecular lines (Reiners & Basri 2007; Shulyak et al. 2011), Zeeman Doppler imaging of M stars (Donati et al. 2008; Morin et al. 2008), as well as numerical simulations of magnetic field generation in fully convective stars (Browning 2008), agree that strong magnetic fields exist across the full range of M-type dwarfs.

Rotation plays a crucial role in all scenarios of magnetic field generation. Observations of activity in solar-type stars show a direct connection between rotation and activity, the so-called rotation–activity relation (Noyes et al. 1984; Delfosse et al. 1998; Pizzolato et al. 2003). Activity grows stronger with increasing rotational velocity and saturates at a threshold velocity that depends on the mass of the star (Pizzolato et al. 2003). The Rossby number \(Ro = P/\tau_{\text{conv}}\), with \(P\) the rotation period and \(\tau_{\text{conv}}\) the convective overturn time, is often used as a unifying scale of activity; activity saturates around \(Ro = 0.1\). A saturation-type rotation–activity relation in M dwarfs is observed for late-M spectral types (later than M5; Mohanty & Basri 2003; Reiners & Basri 2010), and less well studied also in early-M type stars (Delfosse et al. 1998; Reiners & Basri 2007).

In this paper, we concentrate on early- to mid-M dwarfs including the transition from partial to complete convection. We include in our catalog only stars of spectral types M0–M4.5.
We took new observations that we combine with data from the literature. Our sample selection is explained in Section 2, analysis methods are described in Section 4, and discussed in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

2.1. New Observations

The goal of our project is to construct a statistically meaningful, yet neither complete nor unbiased, sample of early-M field dwarf spectra. Literatures available at the time of observations containing considerable samples of high spectral resolution analysis of field-M dwarf rotation velocities were Marcy & Chen (1992) and Delfosse et al. (1998). During the course of our project, Jenkins et al. (2009) and Browning et al. (2010) added more stars to this list, and a few other rotational velocities were presented in Reiners (2007) and Reiners & Basri (2007). We did not exclude young or halo stars from the sample in order to achieve a representative picture of the stars in the solar neighborhood.

Observations for this project were carried out at the spectrographs FOCES (CAHA, Calar Alto) in 2005 and FEROS (ESO, La Silla) in 2006 using time allocated through the Max-Planck Institute for Astronomy (MPIA) at both observatories. In total, we have obtained spectra of 239 M0–M4.5 stars.

2.2. Data Reduction

The FOCES échelle spectrograph at the 2.2 m Telescope at CAHA, Calar Alto, was operated at a spectral resolving power of approximately 40,000. Observations carried out with FEROS at the ESO/MPG 2.2 m Telescope at La Silla have a spectral resolution of approximately 48,000. Typical exposure times are between a few minutes and one hour per star for FEROS and up to two hours with FOCES. Individual exposures are always shorter than 30 minutes to avoid crowding with cosmic rays. The resulting signal-to-noise ratios (S/Ns) are typically around 50; further analysis uncertainties are discussed in Section 4.

Data reduction followed standard procedures including bias subtraction, flat fielding, and wavelength calibration provided by ThAr or ThArNe lamps. For the FEROS spectra, reduction was done with the dedicated pipeline based on the MIDAS context, the FEROS Data Reduction System.

FOCES data were reduced using standard reduction procedures implemented in ESO-MIDAS. To avoid over- or underexposure for different échelle orders, three flat fields were taken with different exposure times, which is the usual procedure for FOCES data reduction. Orders were grouped in three sets each corresponding to different flat-field exposure times, with the longest time corresponding to red and the shortest time to blue regions in the spectrum. All three flat fields were merged to create a master flat field. The raw object spectra were freed from cosmic-ray contamination and, after bias subtraction, flat fielded with the master flat field. The wavelength scale was calibrated for each night using ThAr lamp calibrations. Scattered light was removed using a standard background subtraction routine in ESO-MIDAS. Since FOCES is a fiber-fed spectrograph, the object spectra were first extracted and then divided by the order-extracted master flat field.

3. THE CATALOG

In order to provide a comprehensive collection of currently available information on rotation and activity in early-M dwarfs, we created a catalog of results from high-resolution spectra merging our results with catalogs published earlier and available in the literature. We tried to select work that used data of quality similar to ours and were not selected according to physical parameters of the targets, i.e., we considered only work collecting data from selections of early-M field dwarfs. We limited our study to literature values of the objects in the same spectral range, M0.0–M4.5. Catalogs of this kind are Marcy & Chen (1992), Delfosse et al. (1998), Reiners (2007), Reiners & Basri (2007), Jenkins et al. (2009), and Browning et al. (2010). From Jenkins et al. (2009), we used only their own observations given in their Table 1 since the collection in their Table 3 is rather inhomogeneous and contains work focusing on young stars. We did not include results from the SACY sample (Torres et al. 2006) either since we focus on nearby field stars while the SACY targets form a specifically selected sample of young stars. All works considered provide information on $v\sin i$, but unfortunately quantitative information on Hα emission is not available in all cases.

The distribution of stars as a function of spectral type is shown in Figure 1. In this sample, known spectroscopic binaries are already removed (Section 4.3). In total, the sample consists of 334 M dwarfs of spectral types M0.0–M4.5. Spectra of 206 targets were taken during the course of this project; several of them were already available in the literature. Our observations add 157 new measurements of $v\sin i$ to the full catalog.

The distribution of stars in our sample does not follow the distribution of stars in the solar neighborhood; in comparison to the distribution of M dwarfs, early-type stars are overrepresented in our sample. We compared the distribution of stars in our sample to the mass function in the field reported by Bochanski et al. (2010). We used their system mass function parameterization in the lognormal form. In order to compare our distribution of spectral types to the mass function, we determined the mass of each spectral type bin and calculated the expected number of stars per bin. We assumed the relation between spectral type and effective temperature according to the relation given in Kenyon & Hartmann (1995) and derived the mass from the temperature following the models at 1 Gyr given in Baraffe et al. (1998). For simplicity, we assumed constant bin sizes in mass for our spectral type bins, which is a reasonable approximation in our spectral type regime. For each spectral bin, we derived its range in log $M$ and determined the number of stars within a 12 pc volume as expected from the mass function given in Bochanski et al. (2010). The result is shown as blue circles in Figure 1. A volume-complete sample would include more mid-M stars per spectral bin than early-M stars. If our sample in each bin only contained the nearest stars, our sample would cover the volume out to $\approx 19$ pc for M0 stars and slightly less than 12 pc for M4.5 stars. Although our sample cannot be considered complete out to any given volume, this shows how representative the sample is for the local Galaxy for the different stars contained; with respect to the local mass distribution of stars, early-M stars are overrepresented with respect to mid-M stars.

Our sample probes the local population of M stars. The sample of early-type stars was drawn from a population that extends up to two times further than our mid-M type stars. Since we do not expect significant differences in the properties of rotation and activity as a function of distance (between 10 and 20 pc), we do not expect that this influences the results with respect to a volume-complete local sample. In any case, our results can be interpreted as representative for typical magnitude-limited surveys (as, for example, planet hunting missions will be).
3.1. $v \sin i$

Although the methodologies determining $v \sin i$ employed in the different studies are basically identical, there are some differences in their implementation. The basic idea is to compare the spectrum of a known, slowly rotating star (the template spectrum) with a spectrum of the science target in which the value of $v \sin i$ is to be determined. The template spectrum is convolved with rotational broadening profiles according to a set of different velocities using the scheme described in Gray (2005).

There are in principle two methods used to determine $v \sin i$. The first method is to directly compare a chosen set of individual spectral lines to artificially broadened template spectra. The value of $v \sin i$ is the one providing the best fit. This method is prone to systematic uncertainties induced by a mismatch between the template and science objects’ spectra. The line profiles for comparison must be selected very carefully and systematic differences may occur if different sets of lines are used. This method determining $v \sin i$ was employed by Marcy & Chen (1992), Reiners (2007), Reiners & Basri (2007), and Jenkins et al. (2009). While Marcy & Chen (1992) and Jenkins et al. (2009) used atomic lines at optical wavelength ranges where blending is a serious issue, Reiners (2007) and Reiners & Basri (2007) employed lines of molecular FeH that are relatively free of blends and embedded in a rather well-defined continuum.

The second method to derive values of $v \sin i$ is the so-called cross-correlation technique (Tonry & Davis 1979; Basri et al. 2000). Here, a slowly rotating template star is identified and its spectrum is cross-correlated with a series of the same template spectrum that is artificially broadened according to different rotational velocities. The widths of the correlation functions provide a calibrated measure of the value of $v \sin i$. Then, the target spectrum is cross-correlated with the non-broadened template spectrum and the width of the resulting correlation peak is converted into $v \sin i$ according to the calibration. Spectra are usually divided into several sections (e.g., spectral orders), and cross-correlation functions of individual orders may be averaged, or the median of individually derived $v \sin i$ values from different orders can be used. The latter procedure may also provide an estimate of the uncertainty. This cross-correlation method was employed in the analysis (see Section 4.2) of our new observations and in the work of Delfosse et al. (1998) and Browning et al. (2010).

3.2. Chromospheric Activity

We collected measurements of projected rotational velocities from the literature. Unfortunately, not all literature also provide activity measurements together with rotation, or they provide only information on whether Hα emission is detected or not, but not the value of equivalent width.

Delfosse et al. (1998) and Browning et al. (2010) included values of log $L_{\text{H}\alpha}/L_{\text{bol}}$ in their tables, and we included their results in our catalog. Marcy & Chen (1992) did not provide information on Hα emission. Jenkins et al. (2009) provided only information on whether Hα was detected, and whether they found Hα in absorption in their spectra. If no Hα was detected at all, we calculated upper limits for the stars assuming similar detection thresholds as for our data (see Section 4.1) because the data quality is similar. In cases where Jenkins et al. (2009) found Hα in absorption, we treated these stars as inactive but mark them in our table. Although the existence of Hα in absorption may be an indicator of weak activity (Cram & Mullan 1979), we classified these stars as inactive because all other works only consider Hα emission as an indicator for activity. In those cases where Jenkins et al. (2009) detected Hα in emission, we do not provide any value in our table. The stars can easily be identified in the catalog as those stars from Jenkins et al. (2009) that have no value of log $L_{\text{H}\alpha}/L_{\text{bol}}$ in our catalog.

Normalized luminosities or upper limits of it are available for 244 stars (73% of our total sample of 334).
4. ANALYSIS

Normalized Hα luminosity was calculated for our new spectra as a proxy for chromospheric activity, and projected rotational velocity was determined using the cross-correlation method.

4.1. Chromospheric Activity

Chromospheric activity was measured from Hα emission in our spectra. We estimated the continuum around Hα taking the median of two different regions on either side of Hα line, namely, 6545–6559 Å and 6567–6580 Å. This value was used to normalize the spectra. We integrated the equivalent width of Hα, namely, 6545–6559 Å and 6567–6580 Å. This value was used to normalize Hα luminosity.

Many stars of our sample do not show significant line emission at Hα. We conservatively estimated the detection limit of our spectra to 0.2 Å, which is consistent with the approach of Cayrel (1988) assuming a 3σ detection limit with

$$\sigma_{\text{EqW}} = 1.5 \frac{\text{FWHM}_{\text{line}} \delta_{\text{line}}}{S/N}$$  \hspace{1cm} (1)

and a typical S/N of 50. In this equation, FWHM_{line} is the full width at half-maximum of the expected line and δ_{line} is the size of a resolution element.

Equivalent width is not a suitable indicator of stellar activity because the continuum flux is a steep function of effective temperature. We used PHOENIX model atmospheres (assuming log g = 5.0; Hauschildt et al. 1999) to transform equivalent widths to Hα flux, $F_{\text{Hα}}$, and to determine the flux ratio $F_{\text{Hα}}/F_{\text{bol}}$ using $F_{\text{bol}} = \sigma T^4$. Effective temperatures were derived from spectral type using the conversion given by Kenyon & Hartmann (1995). Finally, we used the identity $F_{\text{Hα}}/F_{\text{bol}} = L_{\text{Hα}}/L_{\text{bol}}$ to determine the ratio between Hα and bolometric luminosity, i.e., normalized Hα luminosity.

4.2. Rotation

In order to derive projected rotational velocities, $v \sin i$, from our spectra, we used the cross-correlation method as mentioned above. As a first step, the spectrum of a slowly rotating star was chosen as a template spectrum and artificially broadened according to a set of different velocities (Gray 2005). We chose velocities in the range [1, 40] km s⁻¹ and limb darkening was set to 0.6 (see Browning et al. 2010). The cross-correlation functions between the unbroadened template spectrum and the set of broadened spectra were calculated and the FWHMs were determined as a function of $v \sin i$. To derive $v \sin i$ in a target spectrum, the cross-correlation function between the object spectrum and the template was calculated; an example is shown in Figure 2. The FWHMs were measured and converted into $v \sin i$ according to the calibration established from the broadened template spectra.

The two spectrographs used for our observations have somewhat different spectral resolving power. In order to avoid systematic differences between the two data sets, we employed different template spectra, i.e., one for each instrument. For the FOCES sample, we used a spectrum of Gl 2 as a template star, and for the FEROS sample, Gl 84 was used. Both objects are of spectral type M2. We tried to use a few different template stars but found no systematic differences.

We estimated the detection limit for rotational broadening from our procedure to determine $v \sin i$. If we artificially broadened the spectra to simulate slow rotation ($v \sin i \lesssim 3$ km s⁻¹), the FWHM of the cross-correlation profile only marginally differed from the autocorrelation function of the template. In our case, the spectral resolving power was not high enough to fully resolve the lines of slow rotators so that the threshold at which significant broadening becomes visible is determined by the spectral resolving power of the instrument. We found that from the FOCES spectra ($R = 40,000$), we can determine values of $v \sin i$ in excess of 4 km s⁻¹. For the FEROS spectra ($R = 48,000$), the detection limit is at $v \sin i = 3$ km s⁻¹.

For the cross-correlation procedure, we used only selected spectral regions that are virtually free of telluric absorption and emission lines. We calculated correlation functions in 13 different spectral regions, each covering approximately 20 Å. The spectral regions are not identical in the FEROS and FOCES samples, which is due to the different performances of the instruments and their coverage of échelle orders.

![Figure 2. Typical cross-correlation profiles. Dashed lines show cross-correlation functions of artificially broadened spectra with the template spectrum. The dark line is the cross-correlation function from an object spectrum with the template spectrum.](image-url)
projected rotational velocity was calculated for each spectral region; the adopted final rotational velocity is the mean of the individual values. The standard deviation for stars with $v \sin i < 20 \text{ km s}^{-1}$ is typically below 1 km s$^{-1}$. Note that this value is much smaller than the detection limit because it is the typical scatter in $v \sin i$ between individual orders while the detection limit is the lowest value of $v \sin i$ at which rotation can be distinguished against other broadening agents like temperature and instrumental broadening. The uncertainty of our $v \sin i$ measurements is also not the same as the intra-order scatter; it is the accuracy at which we can distinguish rotation from other broadening agents; we estimated the final uncertainty to be $\sim 3 \text{ km s}^{-1}$ for slow rotators but not less than 10% (see Reiners 2007; Reiners & Basri 2007).

4.3. Spectroscopic Binaries

Complete information on binarity in stars is difficult to achieve. Binarity may be detected using high spatial resolution imaging, but in many cases binary components are too close to each other and cannot be spatially resolved. In such a case, the observed spectrum consists of light from all components weighted according to their luminosity. If both components are similar in luminosity, both spectra appear in the spectrum with a separation according to the difference in radial velocities at the time of observation. For the search for spectroscopic binaries, the cross-correlation profile is very useful. Three cases can be distinguished. (1) The separation is larger than the typical line width. In such a case, two systems of spectral lines are visible in the spectrum and the cross-correlation profile shows two separated maxima. (2) The separation is on the order of the typical line width. Here, the cross-correlation function is broader than individual correlation maxima due to single stars. The profile may appear asymmetric depending on the luminosity difference of the components and their radial velocity difference. Figure 3 shows a typical cross-correlation profile with significant asymmetry that is attributed to a spectroscopic binary. (3) The separation is marginally different from zero. The profile appears only slightly wider than the typical single profile and may be asymmetric.

If a system is a multiple system instead of a single star, the determination of rotation becomes meaningless unless individual components can be disentangled from each other. We found that 20 stars of our originally observed sample are spectroscopic binaries that could be unambiguously identified. The stars are listed in Table 1 and are not used for further analysis and the catalog. For completeness, Table 1 also includes spectroscopic binaries of spectral types M0.0–M4.5 reported in the literature.

Our cross-correlation analysis revealed that 13 other stars have asymmetric cross-correlation profiles. The degree of asymmetry is small but justifies the assumption that the stars are no regular single objects. They may be spectroscopic binaries with long periods or observed at very similar radial velocities. We excluded these objects from our sample analysis. The marginal outliers are listed in Table 2; further observations at a different epoch may clarify whether these stars are in fact binaries.

5. RESULTS

Our catalog of early- to mid-M dwarfs with measured rotational velocities together with information about activity is given in Table 3. Spectral types are taken from Reid et al. (1995). Information on activity and rotation from our observations and the literature are given as explained in the foregoing sections.

5.1. Chromospheric Activity

In Figure 4, we show normalized Hα activity as a function of spectral type. In total, our catalog contains 244 stars with Hα measurements, 95 of them (39%) are active. It is well established that activity lifetimes are substantially longer at later spectral types (e.g., Hawley et al. 1996; Gizis et al. 2002; Silvestri et al. 2005; West et al. 2008). Stars on the cool side of the boundary to complete convection appear active much longer, leading to the observation that many more fully convective stars show activity. On the hot side of that boundary, where stars are
believed to still harbor a tachocline and hence may drive a Sun-like large-scale dynamo, only very few active stars are known in the field. Virtually all active early-M stars are members of young associations; several examples can be found in Torres et al. (2006). Partially convective early-M stars in the field, however, that are believed to be older, in general do not possess significant activity. Within the literature concerned for our catalog, there is no early-M type star (<M3) with significant activity that is not a known member of a young association. Thus, any single early-M type active star is probably young, which means not older than a few 100 Myr. In fully convective stars, however, activity can persist for several Gyr and we expect to find many more active stars as a function of spectral type is shown in Figure 5; it is in general higher than reported in West et al. (2008) from the Sloan Digital Sky Survey sample, which is consistent with our sample being younger than the sample used there (observed away from the Galactic plane), and our results are consistent with earlier work on the activity fraction of field stars (e.g., Hawley et al. 1996; Gizis et al. 2002; Silvestri et al. 2005). The general trend, however, is very well reproduced. A relatively sharp transition from a low activity fraction smaller than 10% to a significant fraction above 50% occurs among spectral type M3. From activity information alone, we cannot determine the reason for this dramatic increase. West et al. (2008) speculated that longer activity lifetimes may be explained by a transition from a rotationally dependent solar-like dynamo to a rotationally independent turbulent dynamo in which magnetic fields can survive much longer even if the stars are rotating slower. We come back to this point when we discuss the rotation of these stars in Section 5.3.

5.2. Active Early-M Dwarfs

Field stars are believed to be relatively old (~Gyr) and early-M dwarfs (<M3) are in general not observed to be active in the field. In our survey, we found or confirmed activity in 7 out of 129 (5%) early-M targets with Hα measurements. The reason for their activity is probably youth since it is known that early-M dwarfs can be very active at young ages. Young stars are rotating much more rapidly and therefore can generate sufficient magnetism to generate magnetic activity (Pizzolato et al. 2003). A potential reason why a field early-M dwarf can generate activity is the prevention of angular momentum loss because of binarity. Another explanation is that the star is indeed young and entered our survey because it is relatively nearby compared to other young objects. Finally, some stars may be misclassified in spectral type so that they are actually within the regime of M3 or later.

The seven active early-M dwarfs found in our survey are presented in Table 4. Spectral types are between M0 and M2; misclassification may be an issue for the latest targets but is unlikely for all of them. Some of the stars have companions but we did not find evidence for binarity in any of the stars that would sufficiently influence the rotation of the star on Gyr timescales. Most of the objects are probably young objects in the solar neighborhood. We discuss the seven stars individually in the following.

Gl 182 is a young star known as V1005 Ori. The star is contained in the SACY sample (Torres et al. 2006; da Silva et al. 2009) and classified as a member of the β Pictoris young association (10 Myr). It shows substantial activity...
Figure 4. Normalized Hα luminosities as a function of spectral type. Early-M dwarfs (<M3) with significant Hα detections are shown as open circles, all other targets as full circles. Non-detections of Hα are plotted at their detection levels with downward arrows added at their position. Numbers in parentheses show the number of non-detections per spectral bin that are often overplotted at the same position.

Table 3
Catalog of Rotation and Activity in 334 M0–M4.5 Stars

| Name     | α(J2000) | δ(J2000) | Spectral Type | log(L_{Hα}/L_{bol}) | v sin i (km s\(^{-1}\)) | Ref |
|----------|---------|---------|---------------|----------------------|-------------------------|-----|
| LTT 692  | 01 14 33.9 | −53 56 39 | M0.0          | <−4.82               | <3.0                    | (1) |
| LTT 11085| 03 18 38.1 | 32 39 57  | M0.0          | <−4.82               | <4.0                    | (1) |
| Gl 182   | 04 59 34.7 | 01 47 00 | M0.0          | −4.11                | 10.4                    | (1) |
| Gl 353   | 09 31 56.4 | 36 19 16  | M0.0          | ...                 | <2.5                    | (2) |
| Gl 373   | 09 56 08.9 | 62 47 21  | M0.0          | ...                 | <2.5                    | (2) |
| Gl 410   | 11 02 38.2 | 21 58 01  | M0.0          | ...                 | <2.5                    | (2) |
| Gl 424   | 11 19 57.7 | 65 50 33  | M0.0          | ...                 | <2.5                    | (2) |
| Gl 438   | 11 43 18.1 | −51 50 14 | M0.0          | <−4.82               | <3.0                    | (1) |
| Gl 459.3 | 12 19 24.4 | 28 22 55  | M0.0          | ...                 | <3.0                    | (3) |
| Gl 461A  | 12 20 25.4 | 00 34 59  | M0.0          | ...                 | <3.0                    | (3) |

References. (1) This work; (2) Browning et al. 2010; (3) Marcy & Chen 1992; (4) Reiners 2007; (5) Delfosse et al. 1998; (6) Jenkins et al. 2009; (7) Reiners & Basri 2007.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

Table 4
Active Early-M Stars

| Name     | Spectral Type | log(L_{Hα}/L_{bol}) | v sin i (km s\(^{-1}\)) |
|----------|---------------|----------------------|-------------------------|
| Gl 182   | M0.0          | −4.11                | 10.4                    |
| Gl 494   | M0.5          | −3.80                | 9.7                     |
| Steph 546A | M1.5          | −3.89                | 5.3                     |
| Wo 9520  | M1.5          | −3.92                | 6.5                     |
| GJ 2036A | M2.0          | −3.45                | 44.3                    |
| Gl 358   | M2.0          | −4.44                | <3.0                    |
| Gl 569A  | M2.0          | −4.30                | <2.5                    |

(log L_{Hα}/L_{bol} = −4.11) and rapid rotation (v sin i = 10.4 km s\(^{-1}\)).

Gl 494A has a companion of spectral type M7 at a separation of 0.475 (Beuzit et al. 2004), and a planetary candidate companion of spectral type T8–9 at 102″ (Goldman et al. 2010). The secondary component is too faint to influence the rotational profile and our measurement of v sin i is most likely the one of the M0.5 primary alone. Beuzit et al. (2004) determined v sin i = 9.6 km s\(^{-1}\) consistent with our observations. They concluded that the object is not a short-period locked binary but a rapidly rotating, young early-M star (see also Burgasser et al. 2010; Brigham et al. 2011).

Steph 546A (GJ 3331A) is also contained in the SACY survey under the name BD 21 1074A. It is classified as a member of the β Pic association (da Silva et al. 2009) and has a companion pair, BD 21 1074BC.

Wo 9520 (GJ 9520) was observed by Daemgen et al. (2007) using the Altair AO System at Gemini North Observatory. No companion could be detected. Shkolnik et al. (2009) observed the star at two different epochs and found no evidence for RV variability, providing evidence that Wo 9520 is not a binary system. Shkolnik et al. (2009) estimated an age of 15–150 Myr. GJ 2036A (CD-56 1032A) is part of a binary system with two active components. The system is classified as a member of the AB Doradus young association (70 Myr) by da Silva et al. (2009).
Gl 358 is identified as a possible member of the Carina-Near Stream by Zucker et al. (2006), which would imply an age of \( \sim 200 \) Myr.

Gl 569A is accompanied by the brown-dwarf pair Gl 569Bab for which orbital parameters are well determined. Comparison of the colors of Gl 569Bab to theoretical isochrones and color mass diagrams suggest an age of 100–125 Myr, which is probably the same as for Gl 569A. The orbital inclination of Gl 569Bab is \( 32^\circ \pm 4^\circ \).

Figure 5. Fraction of active stars per spectral type in our sample. Numbers show how many stars are measured per spectral bin. Error bars show 1σ uncertainties.

For our catalog, we adopted \( v \sin i \) values according to the following strategy. Preference was given to the \( v \sin i \) data from the work done with the highest spectral resolution. The highest priority was given to the results from Reiners (2007) because they were derived from the highest resolution spectra. The second highest priority was given to the results from Browning et al. (2010). If both were not available and several other works provided measurements of \( v \sin i \), we chose to use the one from our new measurements. In Figure 6, we show a comparison between \( v \sin i \) measured in this work and data from the literature. For all stars, values are consistent within the uncertainties and detection limits.

Projected rotational velocities, \( v \sin i \), for our catalog are plotted as a function of spectral type in Figure 7. The situation appears very similar to the one in Figure 4 where activity
is shown as a function of spectral type. Again, we see only a few early-M type stars with significant rotation (shown as open circles in Figure 7). These stars are listed in Table 4 and discussed individually in Section 5.2. At later spectral types ($\gtrsim$M3), significant rotation appears to be more frequent just as activity is more frequent in this spectral range. In total, 51 of our 334 stars (15%) show rotational broadening of $v \sin i \geq 3$ km s$^{-1}$.

Figure 8 shows the fraction of rapid rotators, i.e., stars with detected rotational broadening $v \sin i \geq 3$ km s$^{-1}$, as a function of spectral type. The figure appears to be very similar to the fraction of active stars discussed above (Figure 5). While among early-M type stars ($<$M3), the fraction of rapid rotators is below 5%; it rises rapidly to approximately 45% at spectral type M4.

5.4. Rotation–Activity Relation

After discussing activity and rotation in the sample catalog, we now turn to the relation between the two across the spectral range M0.0–M4.5, i.e., from partially convective Sun-like stars to fully convective stars. The two distributions in Figures 5 and 8 are strikingly similar. Within statistical uncertainties, the distributions of active and rapidly rotating stars are consistent with the assumption that active stars and rapid rotators are both drawn from the same underlying population. We tested the probability that both distributions are drawn from the same distribution following Kolmogorov–Smirnov statistics (Press et al. 1992). In numbers, the probability that the sample of active stars and the sample of rapidly rotating stars are drawn from independent distributions is lower than $4 \times 10^{-4}$. This means that rotation and activity are highly correlated and that the active stars in our sample are likely the same stars as the rotating ones. While this does not prove a causal relation between rotation and activity, it provides evidence that both occur in the same stars.

It is worth emphasizing that evidence for a correlation between activity and rotation exists over the entire sample including both partially and fully convective stars. In other words, before we discuss the relation between rotation and activity on the basis of individual stars, the distribution of rotation and activity in M0–M4 stars already provides strong evidence for the validity of the rotation–activity connection across the boundary to complete convection.

We plot the normalized Hα luminosity, $\log L_{\text{H}\alpha}/L_{\text{bol}}$, against the projected rotational velocity, $v \sin i$, in Figure 9. In the figure, we further discriminate between partially convective stars ($<$M3) and likely fully convective stars (M3 and later). The boundary between the two groups is likely not sharp and spectral type uncertainties on the order of 0.5–1 spectral subtypes further soften the location of this transition. As a first result, we can confirm the rotation–activity relation in the sense that low activity ($\log L_{\text{H}\alpha}/L_{\text{bol}} < -4.5$) only occurs at slow rotation. There are a handful of inactive stars (stars with low activity) for that detection of rotational line broadening on the order of 4–5 km s$^{-1}$ is detected. We discuss these stars in Section 5.5. Furthermore, we can conclude that the correlation between rotation and activity is valid at both sides of the convection.

### Table 5

| Name   | Spectral Type | $v \sin i$ (km s$^{-1}$) | Adopted |
|--------|---------------|--------------------------|---------|
|        |               | This Work    | (1)     | (2)  | (3)  | (4)  | (5)  | (6)  |
| Gl 424 | M0.0          | ...          | <2.9    | ...  | ...  | ...  | ...  | <2.5 | <2.5 |
| Gl 678.1A | M0.0       | <4.0         | ...     | ...  | <3.0 | ...  | <2.5 | <2.5 |
| Gl 720A | M0.0          | <4.0         | ...     | <3.0 | ...  | ...  | ...  | <3.0 |
| Gl 846 | M0.0          | <3.0         | ...     | ...  | <2.5 | <3.0 |
| Gl 27.1 | M0.5          | <3.0         | ...     | ...  | <2.5 | <3.0 |
| Gl 212 | M0.5          | <3.0         | ...     | <3.0 | ...  | ...  | <3.0 |
| Gl 229 | M0.5          | <3.0         | ...     | <3.0 | ...  | ...  | <3.0 |
| Gl 369 | M0.5          | <3.0         | ...     | ...  | <3.0 |
| Gl 412A | M0.5         | <3.0         | ...     | ...  | <3.0 |
| Gl 494 | M0.5          | 10.7         | ...     | ...  | <2.5 |

**Notes.** Uncertainties are discussed in Sections 4.2 and 5.3.

**References.** (1) Delfosse et al. 1998; (2) Jenkins et al. 2009; (3) Marcy & Chen 1992; (4) Reiners 2007; (5) Reiners & Basri 2007; (6) Browning et al. 2010.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 7. Projected rotational velocity ($v \sin i$) as a function of spectral type. Upper limits in $v \sin i$ are shown with downward arrows. Open circles show early-type M stars ($< M3$) that were found to be rotating faster than $v \sin i = 3 \text{ km s}^{-1}$ (five stars). The numbers in parentheses denote the number of slow rotators per spectral bin in which rotation is below the detection threshold (sum of all stars with downward arrows in this bin).

Figure 8. Fraction of rapid rotators per spectral type in our sample. Rapid rotators are stars with detected rotational broadening at $v \sin i = 3 \text{ km s}^{-1}$ or larger. Numbers show how many stars are measured per spectral bin. Error bars show 1σ uncertainties.

boundary, i.e., for both early- and later-M type stars (open and solid symbols in Figure 9).

Active stars are found at virtually all rotation rates. In our sample, we found 48 very active stars with log $L_{\text{H}\alpha}/L_{\text{bol}} > -4.5$. Among them, 33 stars are rapid rotators ($v \sin i > 3 \text{ km s}^{-1}$). This means that 15 out of 48 active stars (31%) have rotation velocities below our detection limit, or are observed under low inclination angles so that high rotation rates are not detected. In the latter scenario, the most active stars at low $v \sin i$ values are interpreted as stars observed under very low angles $i$. We can test the assumption whether a tight relation between rotation and activity is valid among all our sample stars. If so, all stars with very high Hα emission, say log $L_{\text{H}\alpha}/L_{\text{bol}} > -4.0$, would be rotating at approximately $v \sin i \gtrsim 5 \text{ km s}^{-1}$, which means that at a typical detection threshold of $v \sin i_{\text{lim}} = 3 \text{ km s}^{-1}$, inclination must be such that $\sin i < 0.6 (i < 37^\circ)$. In our sample, 7 out of 36 (19%) stars with log $L_{\text{H}\alpha}/L_{\text{bol}} > -4.0$ show no detectable rotation. In a sample of stars with randomly oriented rotation axes, a fraction of 19% will be observed at inclination angles smaller than 36°, i.e., $\sin i < 0.59$. Thus, we can conclude that the distribution of measurements in $v \sin i$ and activity is consistent with the assumption of a well-defined relation between rotation and activity that is spread out in Figure 9 due to projection effects from observing the stars under statistically distributed orientations.
Active M stars are known to exhibit frequent flaring events that introduce substantial scatter in $\log L_{\text{H}\alpha}/L_{\text{bol}}$ and is difficult to quantify with just one observation. Kowalski et al. (2009) found that among a sample of 236 stars with flares, ~3% show no H$\alpha$ emission outside the flare. If we assume that inactive stars with occasional flaring are slow rotators, we can estimate that 1 star of our 33 slowly rotating flare stars is in fact an inactive, slow rotator. Furthermore, Hilton et al. (2010) determined the flare rates of stars at different spectral types; for stars of our sample the flare rates are $\lesssim$1%. Although it is not trivial to compare the flare rates from Hilton et al. (2010) to our sample because of the inhomogeneous distribution of exposure times, we can exclude a significant influence of flaring on the occurrence of active stars for which no evidence of rotation could be detected.

In Figure 9, we have distinguished between early-M type stars ($<$M3, open symbols) and later M stars (solid symbols) expecting the transition from partially to fully convective stars at this spectral range. The subsample of early-M dwarfs is defined by a number of inactive, slowly rotating stars (with several upper limits in $v\sin i$) and seven active stars, five of them with detected rotation. The early-M dwarfs exhibit a clear correlation between projected rotation rate and normalized H$\alpha$ activity; all stars with $v\sin i \gtrsim 3$ km s$^{-1}$ and above are active, and the stars with $v\sin i \gtrsim 5$ km s$^{-1}$ show higher activity than those at $v\sin i \approx 3$ km s$^{-1}$. Interestingly, the scatter in activity in early-M stars at $v\sin i \gtrsim 5$ km s$^{-1}$ is much smaller than the scatter in mid-M stars in our sample. From our small sample, it is not possible to decide whether this is an intrinsic effect or due to the small number of rapidly rotating early-M stars, but it is consistent with the conclusion of Gizis et al. (2002) and Lee et al. (2010) that the H$\alpha$ variability is larger at later spectral types. In a fully convective star, the scatter of H$\alpha$ activity is much larger than in early-M dwarfs, but as in early-M dwarfs all significantly rotating fully convective stars show significant H$\alpha$ activity. In summary, the saturation-type rotation–activity relation is intact until spectral type M4.5, while the scatter is perhaps growing larger in lower-mass stars that generally tend to be more active in our sample.

### Table 6

| Name     | Spectral Type | $\log(L_{\text{H}\alpha}/L_{\text{bol}})$ | $v\sin i$ (km s$^{-1}$) |
|----------|--------------|------------------------------------------|-------------------------|
| GJ 3104  | M3.0         | $\lesssim$-4.90*                         | 4.0                     |
| LHS 2651 | M3.5         | $\lesssim$-4.93                          | 3.9                     |
| LHS 1785 | M4.5         | $\lesssim$-4.97                          | 4.5                     |
| LHS 1857 | M4.5         | $\lesssim$-4.97                          | 4.0                     |
| GJ 3542  | M4.5         | $\lesssim$-4.97*                         | 3.9                     |
| GJ 1134  | M4.5         | $\lesssim$-4.97*                         | 4.1                     |
| GJ 121-028 | M4.5      | $\lesssim$-4.97*                         | 3.8                     |
| GJ 1186  | M4.5         | $\lesssim$-4.97                          | 3.9                     |
| GI 585   | M4.5         | $\lesssim$-4.97*                         | 3.1                     |

**Notes.** Stars marked with an asterisk show H$\alpha$ in absorption (Jenkins et al. 2009).

**References.** All $v\sin i$ values from Jenkins et al. (2009).

### 5.5. Rapidly Rotating Inactive Stars

The relation between rotation and activity may not be valid in all individual cases. In general, rotation generates magnetic activity, but we may still find activity in some stars that are observed at low projected rotation rates, or even in stars that are slowly rotating but active for reasons we have not understood. On the other hand, our assumption of magnetic dynamo operation triggered by rotation leads to the expectation that all rapidly rotating stars show significant values of magnetic activity. West & Basri (2009) reported the existence of three rapidly rotating but inactive stars at spectral types later than our sample (M6–M7). We searched for such stars in our sample of hotter M stars.

Table 6 lists nine stars in which no H$\alpha$ emission was found but a detection of rotational broadening was reported. All nine stars are from the catalog of Jenkins et al. (2009), and all stars have values of $v\sin i$ between 3 and 4.5 km s$^{-1}$. Four of the nine stars are reported to show H$\alpha$ in absorption, which is evidence for very low but non-zero activity.

Regardless of whether or not the stars with H$\alpha$ absorption are indeed weakly active, it is striking that all nine stars are found
in the same work. Our catalog contains 23 stars taken from Jenkins et al. (2009); 9 of them show no activity in the presence of rotation. Among the 311 stars taken from other sources, not a single star shows similar properties to another star. The spectral resolution of the data used by Jenkins et al. (2009) is \( R = 37,000 \). For such data, a detection limit between 3 and 5 km s\(^{-1}\), which means at the same order as the measurements reported for the stars in Table 6, can be expected depending on S/N. We argue that the absence of rapidly rotating inactive stars in the rest of our sample provides ample evidence that all rapid rotators \( v \sin i \gtrsim 3 \text{ km s}^{-1} \) show measurable H\( \alpha \) activity, and that the reported detections of rotation in inactive stars from Jenkins et al. (2009) are spurious and in fact upper limits to their real values of \( v \sin i \). Our conclusion is that substantial chromospheric emission is a fundamental consequence of rapid rotation in M0–M4.5 stars.

6. COMPARISON TO PHOTOMETRIC PERIODS

Stellar line broadening provides information about the projected rotation velocity on the surface of a star. A more convenient and physically meaningful property is the rotation period of the star. The period \( P \) and projected surface velocity \( v \sin i \) are related through

\[
v \sin i = \frac{2 \pi R \sin i}{P},
\]

with \( R \) the stellar radius. Measuring photometric periods in M dwarfs is notoriously difficult because of the high activity these stars reach even at relatively long periods. This means that spot lifetimes may be shorter than typical rotation periods. We collected photometric periods from Irwin et al. (2011) and Kiraga & Stepień (2007); the latter includes references to period measurements for Gl 411 (Noyes et al. 1984) and Gl 699 (Benedict et al. 1998). Furthermore, we considered periods collected in Messina et al. (2003), namely periods for Gl 410 (Fekel & Henry 2000) and Gl 735 (Alekshev 1998), and periods presented in Engle et al. (2009) including the period of Gl 873 from Contadakis (1995). We augmented our sample of M0.0–M4.5 stars with three additional stars of spectral type M5, GJ 1057, and GJ 1156, for which rotational periods are reported by Irwin et al. (2011), and Gl 551 (period from Kiraga & Stepień 2007), and in which measurements of \( v \sin i \) are available. From the period, we estimated the star’s surface velocity for which information on stellar radius is required. Irwin et al. (2011) provided radius estimates for their targets. For the stars in Kiraga & Stepień (2007; including Gl 411 and Gl 699), we adopted the stellar masses provided there and assumed that stellar radius in solar units has the same value as stellar mass expressed in solar units (i.e., for a star with \( M = 0.5 \, M_\odot \) we assumed \( R = 0.5 \, R_\odot \); see Demory et al. 2009). For the other stars we used the strategy of Kiraga & Stepień (2007), calculating mass from the \( V \)-band mass–luminosity relation in Delfosse et al. (2000) and assumed mass–radius identity as above.

The stars with rotational period measurements are shown in Table 7. For each star, we calculated the equatorial surface velocity, \( v_{\text{eq}} \), derived from the period and compared it to the measured projected surface velocity \( v \sin i \). The two velocities, \( v_{\text{eq}} \) and \( v \sin i \), are compared in the left panel of Figure 10. If period and surface velocity are consistent, the stars should populate the region close to the line of identity (drawn as solid line in Figure 10). Stars observed under low inclination angles \( i \) are expected to fall below that line. Comparing the values \( v_{\text{eq}} \) and \( v \sin i \), we found that several stars are far away from the line of unit slope. From the typical scatter in the mass–luminosity relation, uncertainties in parallax and photometric measurements, and the scatter in the mass–radius identity, we estimated that the final uncertainty in \( v_{\text{eq}} \) is typically much lower than 50%, which translates into uncertainties in the inclination much lower than a factor of two. Therefore, very low inclination angles (below \( \sim 50^\circ \)) are unlikely to be caused by uncertainties in measuring \( v \sin i \) or the translation into \( v_{\text{eq}} \).

Stars with \( v \sin i < v_{\text{eq}} \) may be observed under small inclination angles. For these stars we plot inclination \( i \) as a function of rotation period in the lower right panel of Figure 10. M-type stars with rotation periods on the order of \( P = 10 \) days and longer have surface rotation velocities below the typical detection limits of \( v \sin i \) measurements. These stars are marked with downward arrows in Figure 10. Although we could not determine information about inclination for those stars, the non-detection of rotational broadening means that spectroscopic measurements are consistent with the reported photometric periods. For some stars, however, we found measurements of rotation velocities with \( v \sin i > v_{\text{eq}} \). For all stars with \( v \sin i > v_{\text{eq}} \) (including upper limits in \( v \sin i \)), we calculated the ratio between projected rotation velocities and photometrically derived surface velocity, \( v \sin i / v_{\text{eq}} \), and plot this ratio in the upper right panel of Figure 10. As expected, for very long periods, limited spectral resolving power leads to very large ratios.

The first conclusion from the comparison between photometric periods and projected rotation velocities is that both measurements are consistent for several stars with measured \( v \sin i \) above the detection limit, and the majority of upper limits in \( v \sin i \) are consistent with surface rotation velocities being below the spectroscopic detection limit. There are two groups of stars in which spectroscopic and photometric rotation rates are not consistent. (1) Among the stars with rotation periods shorter than 10 days, seven stars have inclination angles below \( i = 60^\circ \) while eight stars have larger inclination angles but ratios of \( v \sin i / v_{\text{eq}} \) not much larger than 1. The fraction of stars with \( i < 60^\circ \) is 47%, which is consistent with the assumption of random orientation of the rotation axis (leading to an expected fraction of 50% with \( i < 60^\circ \)). On the other hand, several stars have extremely small inclination angles; for example, two stars have \( i < 5^\circ \). The fraction of stars with a such low inclination angle in a sample of randomly oriented spin axes is only 0.4%, yet 14% of the stars in this subsample are found. Thus, the fraction of stars with very low inclination angles appears to be unrealistically low. (2) Three stars exist in our sample in which \( v \sin i \) exceeds \( v_{\text{eq}} \) by a factor of two or higher (marked as red stars in Figure 10). Here, spectroscopic and photometric measurements are clearly inconsistent.

Inconsistencies between spectroscopic and photometric measurements can have several reasons. First, a high frequency of stars observed under very small inclination angles could be due to an observational bias. Photometric periods are most likely to be detected in stars that show large brightness variations. If a star is observed pole-on, brightness variations caused by corotating spots are smaller than if the star is observed under high inclination. This results in a potential bias toward the detection of photometric periods in stars with large values of \( i \). Thus, this bias results in a lower fraction of stars with very small \( i \) than expected from a random distribution of rotation axes. Taking this bias into account, the existence of several stars with very small inclination angles is even more unlikely. Another potential
source of error is incorrect period measurements. Period measurements from Irwin et al. (2011) are based on several hundred data points and show clear periodicity as demonstrated in that paper. The quality of other period reports is generally lower simply because of the exquisite data quality used in Irwin et al. (2011). For example, photometric data used for the Kiraga & Stepien (2007) periods are of much lower quality. Nevertheless, the periods except for GJ 1186 are consistent with spectroscopic and photometric measurements is an incorrect estimate of $v \sin i$. This is a likely explanation for one of our cases: GJ 1186 has $v \sin i = 3.9 \text{ km s}^{-1}$ exceeding $v_{eq}$ by a factor of 40. Here, the phase-folded light curve presented by Irwin et al. (2011) looks very reasonable. The value of $v \sin i$ is from the catalog of Jenkins et al. (2009) and similar to the values shown in Table 6 for which we argued that these measurements are upper limits rather than detections. We argue that this measurement is probably an upper limit, too. This point is strengthened by the fact that the period measurements from the catalog of Irwin et al. (2011, solid points in Figure 10) seem to be rather robust—all periods except for GJ 1186 are consistent with $v \sin i$ data.

A third potential reason for inconsistencies between spectroscopic and photometric measurements is an incorrect estimate of $v \sin i$. This is a likely explanation for one of our cases: GJ 1186 has $v \sin i = 3.9 \text{ km s}^{-1}$ exceeding $v_{eq}$ by a factor of 40. Here, the phase-folded light curve presented by Irwin et al. (2011) looks very reasonable. The value of $v \sin i$ is from the catalog of Jenkins et al. (2009) and similar to the values shown in Table 6 for which we argued that these measurements are upper limits rather than detections. We argue that this measurement is probably an upper limit, too. This point is strengthened by the fact that the period measurements from the catalog of Irwin et al. (2011, solid points in Figure 10) seem to be rather robust—all periods except for GJ 1186 are consistent with $v \sin i$ data.

### Table 7

| Name      | Spectral Type | $P$ (days) | Ref. | $v_{eq}$ (km s$^{-1}$) | $v \sin i$ (km s$^{-1}$) | Ref. | $i$ (°) | Exceed |
|-----------|---------------|------------|------|------------------------|-------------------------|------|---------|--------|
| GI 182    | M0.0          | 4.4 (ks)   |      | 7.9                    | 10.4                    |      |         | 1.3    |
| GI 410    | M0.0          | 14.8 (fh)  |      | 2.0                    | <2.5                    |      |         | (2)    |
| GI 424    | M0.0          | 149.7 (en) |      | 0.2                    | <2.5                    |      |         | (2)    |
| GI 494    | M0.5          | 2.9 (ks)   |      | 9.8                    | 9.7                     |      |         | (2)    |
| Steph 546A|M1.5          | 0.3 (ks)   |      | 74.2                   | 53                      |      |         | (1) 4  |
| GI 205    | M1.5          | 33.6 (ks)  |      | 0.9                    | 1.5                     |      |         | (4)    |
| GI 382    | M1.5          | 21.6 (ks)  |      | 1.2                    | 1.8                     |      |         | (4)    |
| Wo 9520   | M1.5          | 0.4 (ks)   |      | 69.9                   | 6.5                     |      |         | (1) 5  |
| GI 2036A  | M2.0          | 0.8 (ks)   |      | 22.6                   | 44.3                    |      |         | (1) 2  |
| GI 358    | M2.0          | 25.3 (ks)  |      | 0.8                    | <3.0                    |      |         | (1)    |
| GI 411    | M2.0          | 48.0 (no)  |      | 0.5                    | <2.5                    |      |         | (2)    |
| GI 569A   | M2.0          | 13.7 (ks)  |      | 1.7                    | <2.5                    |      |         | (2)    |
| GI 84     | M2.5          | 44.5 (ks)  |      | 0.5                    | <3.0                    |      |         | (1)    |
| GI 674    | M2.5          | 33.3 (ks)  |      | 0.6                    | <3.0                    |      |         | (1)    |
| GI 388    | M3.0          | 2.2 (en)   |      | 8.2                    | 3.0                     |      |         | (4) 21 |
| GI 735    | M3.0          | 2.9 (al)   |      | 9.0                    | 7.7                     |      |         | (1) 58 |
| GI 431    | M3.5          | 14.3 (ks)  |      | 1.2                    | 20.5                    |      |         | (1) 17.6|
| GI 669A   | M3.5          | 0.9 (ks)   |      | 18.6                   | <4.0                    |      |         | (1) 12 |
| GI 729    | M3.5          | 2.9 (ks)   |      | 3.5                    | 4.0                     |      |         | (2) 1.1 |
| GI 873    | M3.5          | 4.4 (co)   |      | 3.4                    | 3.5                     |      |         | (2) 1.0 |
| G 099-049 | M4.0          | 1.8 (ir)   |      | 7.3                    | 7.4                     |      |         | (5) 1.0 |
| GI 699    | M4.0          | 130.0 (be) |      | 0.1                    | <2.5                    |      |         | (2)    |
| GI 1243   | M4.0          | 0.6 (ir)   |      | 22.2                   | 22.0                    |      |         | (1) 83 |
| GI 876    | M4.0          | 116.5 (en) |      | 0.1                    | <2.5                    |      |         | (2)    |
| LHS 1885  | M4.5          | 52.4 (ir)  |      | 0.2                    | <3.7                    |      |         | (5)    |
| GI 285    | M4.5          | 2.8 (ir)   |      | 5.8                    | 4.5                     |      |         | (4) 50 |
| GI 1151   | M4.5          | 132.0 (ir) |      | 0.1                    | <4.1                    |      |         | (5)    |
| GI 493.1  | M4.5          | 0.6 (ir)   |      | 16.0                   | 16.8                    |      |         | (5) 1.0 |
| GI 1186   | M4.5          | 88.3 (ir)  |      | 0.3                    | 3.9                     |      |         | (6) 40.1|
| GI 791.2  | M4.5          | 0.3 (ir)   |      | 33.6                   | 32.0                    |      |         | (5) 72 |
| GI 1057   | M5.0          | 102.0 (ir) |      | 0.1                    | <2.2                    |      |         | (5)    |
| GI 1156   | M5.0          | 0.5 (ir)   |      | 16.5                   | 9.2                     |      |         | (5) 33 |
| GI 551    | M5.5          | 82.5 (ks)  |      | 0.1                    | <3.0                    |      |         | (8)    |

**References.** Period references: (ks) Kiraga & Stepien 2007; (fh) Fekel & Henry 2000; (no) Noyes et al. 1984; (al) Alekseev 1998; (be) Benedict et al. 1998; (ir) Irwin et al. 2011; (en) Engle et al. 2009; (co) Contadakis 1995. $v \sin i$ references: (1) this work; (2) Browning et al. 2010; (3) Marcy & Chen 1992; (4) Reiners 2007; (5) Delfosse et al. 1998; (6) Jenkins et al. 2009; (7) Reiners & Basri 2007; (8) Reiners & Basri 2008.
in stars close to the transition between partial and complete convection.

In addition, we identify 12 spectroscopic binaries plus 8 binaries that were already known from earlier work and re-observed for our project. Thirteen other stars were found to show peculiar line profiles perhaps due to binarity. These 33 stars are not contained in the catalog and presented individually.

We investigate rotation and activity in our sample stars with an emphasis on the transition from partial to complete convection occurring around spectral type M3. We confirm that the fraction of active stars is very low in early-M stars (<M3) and rises steeply around spectral type M3. For the seven active early-M field stars in our sample, we find evidence that all are younger than a few hundred Myr. Furthermore, we find that the behavior of the fraction of rapidly rotating stars with respect to spectral class is virtually identical to the fraction of active stars, which provides strong support to the assumption that all active stars are rapid rotators. A detailed analysis of the rotation–activity relation supports this picture. We argue that in a few individual cases reports of rotational broadening in the absence of Hα emission are spurious and that these detections are in fact upper limits of $v \sin i$. We conclude that all rapid rotators ($v \sin i > 3 \text{ km s}^{-1}$) are active ($\log L_{\text{H\alpha}}/L_{\text{bol}} > -4.5$). There is no significant difference between rotation–activity relations on both sides of the convection boundary. An important result is that the distribution of activity in early- to mid-M dwarfs can entirely be explained by rotational braking. This implies that at the boundary to complete convection, we do not observe any evidence for a transition from a rotationally dominated dynamo to a turbulent dynamo independent of rotation. This does not imply that the predominant dynamo mechanism does not change, but shows that the dynamo in fully convective stars at spectral types M3.0–M4.5 is still driven by rotation.

Scatter in the rotation–activity diagram appears to be different between early-M and later stars (M3.0–M4.5). Early-M stars show less scatter in activity while large scatter is observed in the later ones. The difference, however, is statistically not well defined because the early-M sample consists of five detections in $v \sin i$ only, and the distribution of the slowest rotators among the most active stars among the later-M sample is consistent with a random distribution of rotation axes. Some stars may also have been observed during short-time flares.

We compare projected rotation velocities to photometric periods taken from several catalogs. Inclination angles of a few rapid rotators are reported: most of the stars with rotation periods longer than $P = 10$ days have rotation velocities $v \sin i$ below our detection limit and are consistent with very slow rotation. We identify a few cases where $v \sin i$ and $P$ are inconsistent: in four or five cases the rotation periods are probably misidentifications; in one case the $v \sin i$ measurement probably is an upper limit rather than a detection.

Our catalog presents a comprehensive database for understanding the evolution of low-mass stars and the connection between rotation and magnetic activity. The latter is considered an important factor for the development of life on habitable planets, for which early-M dwarfs have become a prominent target sample. The potential to detect extrasolar planets depends on the width of the stellar line profiles, and our catalog provides important input selecting target samples for future radial velocity surveys for planets around low-mass stars.

Based on observations collected at the Centro Astronómico Hispano Alemán (CAHA) at Calar Alto, operated jointly by the Max-Planck Institut für Astronomie and the Instituto de Astrofísica de Andalucía (CSIC), and on observations obtained from the European Southern Observatory on MPI time under PID 076.A-9005. A.R. acknowledges financial support from the Deutsche Forschungsgemeinschaft (DFG) under an Emmy Noether fellowship (RE 1664/4-1) and a Heisenberg Professorship (RE 1664/9-1). N.J. acknowledges the support from the DFG Research Training Group GrK-1351 “Extrasolar Planets and their Host Stars.” This work was supported by Sonderforschungsbereich SFB 881 “The Milky Way System” (subproject B6) of the DFG.

Figure 10. Left panel: projected rotational velocity $v \sin i$ against surface equatorial velocity $v_{\text{eq}}$ calculated from photometric period. Right panel: inclination angle derived from the comparison between $v \sin i$ and $v_{\text{eq}}$ if $v \sin i < v_{\text{eq}}$ (lower panel), and ratio $v \sin i/v_{\text{eq}}$ if $v \sin i > v_{\text{eq}}$ (upper panel). Downward arrows indicate upper limits in all values that are due to upper limits in $v \sin i$. Solid symbols are period measurements from Irwin et al. (2011), open circles are from Kiraga & Stepien (2007), and open squares are taken from other literature (see the text). Three stars with $v \sin i > v_{\text{eq}}$ in which $v \sin i$ is not an upper limit are shown as red stars.
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