Calibration of the Hα Age–Activity Relation for M Dwarfs

Rocio Kihan1,2,3, Jacqueline K. Faherty2, Kelle L. Cruz1,2,3,4, Jonathan Gagne5,6, Ruth Angus2,4,7, Sarah J. Schmidt8, Andrew W. Mann9, Daniella C. Bardalez Gagliuffi5, and Emily Rice1,2,10

1 Department of Physics, Graduate Center, City University of New York, 365 5th Avenue, New York, NY 10016, USA; rociokihan@gmail.com
2 Department of Astrophysics, American Museum of Natural History, Central Park West at 79th Street, New York, NY 10024, USA
3 Hunter College, City University of New York, 695 Park Avenue, New York, NY 10065, USA
4 Center for Computational Astrophysics, Flatiron Institute, 162 5th Avenue, New York, NY 10010, USA
5 Planétarium Rio Tinto Alcan, Espace pour la Vie, 4801 av. Pierre-de-Coubertin, Montréal, Québec, Canada
6 Institute for Research on Exoplanets, Université de Montréal, Département de Physique, C.P. 6128 Succ. Centre-ville, Montréal, QC H3C 3J7, Canada
7 Department of Astronomy, Columbia University, 116th Street & Broadway, New York, NY 10027, USA
8 Leibniz-Institute for Astrophysics Potsdam (AIP), An der Sternwarte 16, D-14482, Potsdam, Germany
9 Department of Physics and Astronomy, The University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, USA
10 Macaulay Honors College, City University of New York, 35 W. 67th Street, New York, NY 10024, USA

Received 2020 August 14; revised 2021 March 29; accepted 2021 March 30; published 2021 May 21

Abstract

In this work, we calibrate the relationship between Hα emission and M dwarf ages. We compile a sample of 892 M dwarfs with Hα equivalent width (Hα EW) measurements from the literature that are either comoving with a white dwarf of known age (21 stars) or in a known young association (871 stars). In this sample we identify 7 M dwarfs that are new candidate members of known associations. By dividing the stars into active and inactive categories according to their Hα EW and spectral type (SpT), we find that the fraction of active dwarfs decreases with increasing age, and the form of the decline depends on SpT. Using the compiled sample of age calibrators, we find that Hα EW and fractional Hα luminosity (LHα/Lbol) decrease with increasing age. Hα EW for SpT ≤ M7 decreases gradually up until ∼1 Gyr. For older ages, we found only two early M dwarfs that are both inactive and seem to continue the gradual decrease. We also found 14 mid-type M dwarfs, out of which 11 are inactive and present a significant decrease in Hα EW, suggesting that the magnetic activity decreases rapidly after ∼1 Gyr. We fit LHα/Lbol versus age with a broken power law and find an index of −0.11±0.02 for ages ≤776 Myr. The index becomes much steeper at older ages, but a lack of field age-calibrators (∼1 Gyr) leaves this part of the relation far less constrained. Finally, from repeated independent measurements for the same stars, we find that 94% of them have a level of Hα EW variability ≤5 Å at young ages (<1 Gyr).

Unified Astronomy Thesaurus concepts: Low mass stars (2050); Astronomy data analysis (1858); Catalogs (205); Stellar activity (1580); Astrometric binary stars (79); Stellar evolution (1599)

Supporting material: machine-readable tables

1. Introduction

M dwarfs are the coolest and most abundant stars in the Milky Way (Gould et al. 1996; Bochanski et al. 2010). As the lifetime of M dwarfs is longer than the current age of the universe (e.g., Fagotto et al. 1994; Laughlin et al. 1997), those that we find throughout the Galaxy span a wide range of ages. Therefore M dwarfs are a rich stellar population for a statistical analysis of the Milky Way evolution, dynamics, and composition (e.g., Gizis et al. 2002; Bochanski et al. 2007, 2010; Faherty et al. 2009; Jones et al. 2011). In addition, M dwarfs are attractive targets for studying exoplanet populations because the occurrence of small rocky exoplanets is higher for M dwarfs than any other spectral type. Furthermore, it is easier to detect small planets around low-mass stars than around higher-mass stars due to the large reflex motion (e.g., Dressing & Charbonneau 2015; Mulders et al. 2015; Shields et al. 2016).

M dwarfs are intrinsically faint, especially toward later and cooler spectral types. Measuring their fundamental properties can therefore be challenging, even for the nearest ones (e.g., Ribas et al. 2017). However, several fundamental properties of M dwarfs have been studied extensively. For instance, using spectroscopy, photometry, and astrometry, effective temperature (e.g., Mann et al. 2015; Ness et al. 2015; Birky et al. 2020), radius (e.g., Kesseli et al. 2018), and luminosity (e.g., Reid & Cruz 2002), metallicity (e.g., Bochanski et al. 2013; Newton et al. 2014; Schmidt et al. 2016) and mass (e.g., Boyajian et al. 2012; Mann et al. 2019) measurements have been studied. Age, however, is one of the most difficult fundamental properties to evaluate, especially for M dwarfs (Soderblom 2010).

Current age-dating methods used for higher-mass stars cannot be applied to low-mass stars. Asteroseismology (e.g., Chaplin et al. 2014) is a common age-dating method for giant stars but cannot be applied to M dwarfs because their acoustic oscillations have extremely small amplitudes and short timescales (Rodríguez et al. 2016). Isochrones from stellar evolution models are not efficient either for estimating M dwarf ages due to the extremely slow and small changes in luminosity after 1 Gyr, making the isochrones very similar for older ages (Chabrier & Baraffe 1997). Furthermore, there are not sufficient empirical calibrations to validate isochrones for low-mass stars, especially at young ages. As a consequence, model isochrones still suffer from significant systematic errors that are unexplored and are inaccurate for precise age determinations (Baraffe et al. 2015). Empirical methods such as gyrochronology (e.g., Skumanich 1972; Barnes 2003, 2007; Angus et al. 2015; Van Saders et al. 2016) are either based on the Sun or are calibrated on higher-mass stars, and they do not
yield precise age estimates for M dwarfs (e.g., Angus et al. 2019). As currently available methods cannot be used to estimate M dwarf ages, empirically calibrated relations for age-related properties are needed.

Magnetic activity, age, and rotation period are known to be correlated for solar-type stars (e.g., Skumanich 1972; Barry 1988; Soderblom et al. 1991; Mamajek & Hillenbrand 2008). These stars have a radiative core and a convective envelope, and they do not rotate as a rigid body. As solar-type stars rotate, a magnetic dynamo is generated in between the two layers, which is responsible for their magnetic field (Parker 1955).

Given that rotation and age are correlated for solar-type stars (e.g., Skumanich 1972; Barnes 2003, 2007; Angus et al. 2015; Van Saders et al. 2016), their magnetic activity is correlated with age as well. For the lowest-mass stars (spectral type >M3), the correlation between magnetic activity, age, and rotation is not well understood because these cool stars are fully convective (Chabrier & Baraffe 1997) and do not have an interface to produce a dynamo. However, previous studies of M dwarfs indicate that magnetic activity, rotation, and age are correlated (e.g., Eggen 1990; Fleming et al. 1995; Delfosse et al. 1998; Mohanty & Basri 2003; West et al. 2004, 2015; Reiners et al. 2012; Newton et al. 2017; Riedel et al. 2017; Angus et al. 2019; Kiman et al. 2019).

A well-studied magnetic activity indicator in M dwarfs is the Hα emission line (Hawley et al. 1996; West et al. 2008a, 2008b), which is generated by collisional excitations when magnetic field lines heat the dense chromosphere (Stauffer & Hartmann 1986). Therefore the Hα equivalent width (Hα EW) is an indirect measurement of the chromospheric magnetic activity of a star. The fact that M dwarf magnetic fields are driven by the stellar rotation means that the rotation-age correlation should translate into a Hα EW-age correlation (Newton et al. 2017). As a consequence, Hα EW could be used as an age indicator for M dwarfs. For low-mass stars, previous studies have confirmed that Hα emission is correlated with age by using kinematics as an age indicator (Gizis et al. 2002; West et al. 2008b; Kiman et al. 2019). West et al. (2008a) found a functional form for the age–activity relation from a sample of M dwarfs with Hα EW by modeling the relation between kinematics and age. However, to date, a study that empirically calibrates the age–activity relation for M dwarfs is still lacking.

A first necessary step for calibrating the Hα age–activity relation is to collect M dwarfs with known ages that are calculated with methods independent of the magnetic activity. The second data release of Gaia (Gaia Collaboration et al. 2016, 2018; Arenou et al. 2018; Lindegren et al. 2018) plays a key role in age-dating stars. The Gaia DR2 catalog contains ∼1.3 billion sources with a five-parameter astrometric solution: positions, parallaxes (π), and proper motions (μ) with unprecedented precision, down to a magnitude of G = 21. The parallax uncertainties (σπ) are between 0.04 and 0.7 mas, and for proper motion (σμ), the uncertainties are between 0.06 and 1.2 mas yr−1, depending on the magnitude of the star. With these high-quality measurements, Gaia made it possible to identify new stars that belong to age-calibrated moving groups and new associations (e.g., Faherty et al. 2018; Gagné & Faherty 2018; Kounkel & Covey 2019; Röser & Schilbach 2020), and new comoving pairs of stars (e.g., Oh et al. 2017; El-Badry & Rix 2018). Both young associations and comoving pairs can be sources for M-dwarf ages.

Moving groups and other coeval associations are ensembles of stars that are born from the same molecular cloud with common space velocities and a small spread of ages (Bell et al. 2015). As ages of the young associations are well calibrated down to a precision of a few million years (Soderblom 2010; Bell et al. 2015), the age of the association can be used to build a set of age-calibrated M dwarfs, if the stars can be identified as members.

Binary stars are born from the same molecular cloud at the same time (Bodenheimer 2011). Therefore we can calibrate the age of an M dwarf by constraining the age of a comover. For example, we can estimate a white dwarf’s total age by adding the white dwarf cooling age and the main-sequence age of the progenitor star (Fouesneau et al. 2018). The white dwarf cooling age and mass are strongly constrained by cooling tracks from theoretical models (e.g., Bergeron et al. 1995, 2019; Fontaine et al. 2001). Using the mass of the white dwarf and the semiempirical initial-to-final mass relations (Cummings et al. 2018), we can estimate the mass of the progenitor star. Finally, with the mass of the progenitor star, we can calculate a main-sequence age, combined with the length of the pre- and post- (but pre-white dwarf) main-sequence stages (obtained with MESA models, Dotter 2016).

The aim of the present study is to calibrate the Hα age–activity relation for M dwarfs using a sample of age calibrators. We describe how we compiled a sample of M dwarfs with Hα EW measurements in the literature in Section 2. We show how we obtained the age calibrators from that sample by identifying M dwarfs that are comoving with a white dwarf with known age or members of known young associations in Section 3. The final table of age calibrators is described in Table 1. In Section 4 we describe the calculation of the fractional Hα luminosity from Hα EW for the age calibrators, which is a key parameter for calibrating the age–activity relation. In this section we also describe a search for known unresolved binaries that might bias our calibration of the age–activity relation. In Section 5 we show how we divided the sample of age calibrators into active or inactive objects according to their Hα EW measurement and photometry, and how we studied the relation between the active fraction and age for different spectral types. In Section 6 we discuss the relation between the Hα EW and fractional Hα luminosity with age and fit it using a Markov chain Monte Carlo (MCMC) algorithm. In Section 7 we compare our results for the age–activity relation with literature results for Hα, X-ray, and UV. Finally, in Section 8 we discuss our results and summarize our work and conclusions. All the code used in this work is available on Zenodo (Kiman 2021) and GitHub.11

2. Identifying M Dwarfs in the Literature with Hα Measurements

2.1. Compiling the Literature Search Sample

In order to empirically calibrate the age–activity relation for M dwarfs, we began by collecting M0-M9 dwarfs from the literature with a reported Hα EW. Kiman et al. (2019) compiled one of the largest published samples of M dwarfs with Hα EW, including measurements from West et al. (2011) and Schmidt et al. (2015). This sample contains 74,216 M dwarfs, 486 of which were removed because they have a spectroscopically

11 https://github.com/rkiman/M-dwarfs-Age-Activity-Relation
identified but unresolved white dwarf companion (West et al. 2011; Schmidt et al. 2015), which could increase the magnetic activity of the star (Skinner et al. 2017). The remaining 73,730 M dwarfs from Kiman et al. (2019) make up the largest part of our literature search sample.

The M dwarfs in Kiman et al. (2019) are assumed to be primarily field stars. We complemented this sample with studies of M dwarfs in known star-forming regions, clusters, moving groups, or M dwarfs that are comoving with a white dwarf, as well as all the studies in the literature that have a measured Hα EW for cool dwarfs. All the studies we checked are listed or mentioned in Table 2. In total, we identified 89,270 stars from the literature (73,730 from Kiman et al. 2019 and 15,540 from other studies). From the total number of stars in our sample, we found that 86,918 stars (97%) have photometric and astrometric information from Gaia DR2 (Gaia Collaboration et al. 2016, 2018). We applied the quality cuts described in Kiman et al. (2019) to select the best astrometric and photometric data from Gaia DR2 (the Sub Red sample). These cuts not only select best-quality photometry, parallaxes, and proper motions, but also remove possible unresolved binaries. We refer to Section 2.3 of Kiman et al. (2019) for more details. By applying these quality cuts, we were left with 27,201 M dwarfs (31%) in our literature search sample. In Section 3 we describe the cross-match with Gaia in more detail. We use the spectral type classification from the literature when available and estimate the spectral type for the remaining stars (6% of the sample) using their Gaia red color (G − G_BP) and the relation in Kiman et al. (2019). Although most of the studies we compiled were focused on M dwarfs, some contained higher-mass stars, mostly G and K dwarfs, which were removed with a cut in spectral type, keeping 25,720 M dwarfs (≥M0).

From our literature search sample, 726 M dwarfs have between two and six measurements of Hα EW. We identified duplicates through a position search within a 2′0 radius. These duplicated stars are indicated in the column star_index in Table 1. If two or more stars have the same number in this column, then they likely are the same star. In total, we found

---

Table 1

| Column name                  | Units    | Description                                           |
|------------------------------|----------|-------------------------------------------------------|
| ra                           | deg      | Original R.A. from the source of the Hα measurement  |
| dec                          | deg      | Original Decl. from the source of the Hα measurement |
| spt                          |          | Spectral type                                         |
| gaia_source_id               |          | Unique Gaia source identifier (unique within DR2)     |
| ra_gaia                      | deg      | R.A. in Gaia DR2 epoch                                |
| dec_gaia                     | deg      | Decl. in Gaia DR2 epoch                               |
| pmra                         | mas yr⁻¹ | Proper motion in R.A. direction in Gaia DR2           |
| pmra_error                   | mas yr⁻¹ | Standard error of proper motion in R.A. direction in Gaia DR2 |
| pmdec                        | mas yr⁻¹ | Proper motion in decl. direction in Gaia DR2          |
| pmdec_error                  | mas yr⁻¹ | Standard error of proper motion in decl. direction in Gaia DR2 |
| parallax                     | mas      | Parallax in Gaia DR2                                  |
| parallax_error               |          | Standard error of parallax in Gaia DR2                |
| phot_g_mean_flux             | electron s⁻¹ | G-band mean flux                                     |
| phot_g_mean_flux_error       | electron s⁻¹ | Error on G-band mean flux                           |
| phot_g_mean_mag              | mag      | G-band mean magnitude                                 |
| phot_rp_mean_flux            | electron s⁻¹ | Integrated GRP mean flux                            |
| phot_rp_mean_flux_error      | electron s⁻¹ | Error on the integrated GRP mean flux                |
| phot_rp_mean_mag             | mag      | Integrated GRP mean magnitude                        |
| phot_bp_mean_flux            | electron s⁻¹ | Integrated G_BP mean flux                          |
| phot_bp_mean_flux_error      | electron s⁻¹ | Error on the integrated G_BP mean flux                |
| g_corr                       | mag      | G magnitude corrected for extinction                 |
| rp_corr                      | mag      | G_BP magnitude corrected for extinction              |
| ewha                         | Å        | Equivalent width Hα for the compatible literature search |
| ewha_error                   | Å        | Equivalent width Hα error for the compatible literature search |
| ewha_all                     | Å        | Equivalent width Hα for all the stars                |
| ewha_error_all               | Å        | Equivalent width Hα error for all the stars          |
| lhalbol                      |          | Fractional Hα luminosity                             |
| lhalbol_error                |          | Fractional Hα luminosity error                       |
| age                          | yr       | Age of the star                                      |
| age_error_low                | yr       | Lower bound on the confidence interval of the estimated age |
| age_error_high               | yr       | Upper bound on the confidence interval of the estimated age |
| group_num                    |          | Number identifying the young association. 0 indicates a white dwarf companion |
| group_name                   |          | Young association to which the star belongs          |
| star_index                   |          | Number indicating repeated stars. Same stars have the same number |
| source_num                   |          | Number indicating the source of the Hα measurement  |
| source_ref                   |          | Source of the Hα measurement                         |
| potential_binary             |          | 1 if it is a potential binary, 0 if not.             |

(This table is available in its entirety in machine-readable form.)

---

12 A catalog resulting from this literature search is available as a FITS table on Zenodo: doi:10.5281/zenodo.4659293.
Table 2
Age Calibrator Summary

| References          | Spectral Resolution | N of M Dwarfs | OC | Ages from |
|---------------------|---------------------|---------------|----|-----------|
|                     |                     | Total         | Compatible | Moving Group | White Dwarf |
| Kiman et al. (2019) | 1800                | 73729         | 73729 | 0          | 46          | 21          |
| LG1                  | 1000                | 2304          | 134   | 2          | 48          | ...         |
| Jeffers et al. (2018)| 62000, 48000, 40000 | 2133          | 2     | 2          | 22          | ...         |
| Douglas et al. (2014)| 3300, 4000         | 1906          | 50    | 1          | 264         | ...         |
| Lepine et al. (2013) | 2000, 4000         | 1577          | 1     | 2          | 4           | ...         |
| Riaz et al. (2006)  | 1750                | 1098          | 4     | 2          | 65          | ...         |
| Ansdel et al. (2015) | 1000, 1200         | 794           | 35    | 2          | 31          | ...         |
| Gaidos et al. (2014) | 1200                | 582           | 59    | 2          | 2           | ...         |
| Fang et al. (2018)  | 1800                | 561           | 1     | 1          | 159         | ...         |
| Newton et al. (2017) | 3000                | 456           | 14    | 2          | 2           | ...         |
| Terrien et al. (2015)| 2000                | 351           | 13    | 2          | 2           | ...         |
| Reid et al. (1995)  | 2000                | 343           | 4     | 2          | 1           | ...         |
| Schneider et al. (2019)| 32000             | 336           | 10    | 2          | 26          | ...         |
| Bouy & Martin (2009)| Multiple            | 227           | 1     | 2          | 135         | ...         |
| Kraus et al. (2014) | 35000               | 205           | 2     | 2          | 88          | ...         |
| Shkolnik et al. (2009)| 60000             | 184           | 7     | 2          | 9           | ...         |
| Alonso-Floriano et al. (2015)| 1500         | 179           | 8     | 2          | 3           | ...         |
| Slesnick et al. (2008)| 1250               | 145           | 69    | 2          | 23          | ...         |
| Malo et al. (2014a)| 1750                | 120           | 1     | 2          | 45          | ...         |
| Torres et al. (2006)| 50000, 9000        | 114           | 2     | 2          | 18          | ...         |
| Shkolnik et al. (2017)| 35000, 58000      | 106           | 3     | 2          | 24          | ...         |
| Elliott et al. (2016)| 85000, 48000      | 83            | 2     | 2          | 3           | ...         |
| Reiners & Basri (2010)| 31000            | 73            | 2     | 1          | 2           | ...         |
| Slesnick et al. (2006)| 1250              | 65            | 19    | 2          | 18          | ...         |
| Jayawardhana et al. (2006)| 60000         | 52            | 1     | 2          | 20          | ...         |
| Riedel et al. (2014)| Multiple           | 50            | 3     | 2          | 5           | ...         |
| Hawley et al. (1996)| 2000               | 31            | 1     | 2          | 1           | ...         |
| Song et al. (2003)  | 24000              | 25            | 1     | 2          | 3           | ...         |
| Rodriguez et al. (2014)| 3000, 7000        | 23            | 12    | 2          | 12          | ...         |

Notes.

a. Compatible catalogs without age calibrators: Gizis et al. (2002), Mochnacki et al. (2002), Reid & Cruz (2002), West et al. (2011), Song et al. (2004), Lyo et al. (2004). Catalogs with overlap but not compatibles: Mohanty et al. (2005), Shkolnik et al. (2011), Lawson et al. (2002). Catalogs without overlap: Frasca et al. (2018), Bayo et al. (2012), Reid et al. (2007), Cruz & Reid (2002), Feigelson et al. (2003), Gizis et al. (2000), Gizis & Reid (1997), Murphy et al. (2010), Phan-Bao & Bessell (2006), Bochanski et al. (2005), Mohanty & Basri (2003), Reiners & Basri (2007, 2008), Lépine et al. (2003, 2009), Martin & Kun (1996), Ivanov et al. (2015), Stauffer et al. (1997), Tinney & Reid (1998). Other catalogs checked: Lodieu et al. (2005).

b. Compatible with Kiman et al. (2019).

c. Order of compatibility. Order 1 is compatible with Kiman et al. (2019). Order 2 is compatible with at least one order 1 catalog.

d. Lepine et al. (2013) and Gaidos et al. (2014) with additional data observed in an identical manner.

that our literature search sample has 24,330 unique M dwarfs with good data from Gaia DR2 and Hα EW measurements.

2.2. Identifying Compatible Hα Measurements from the Literature

The Hα EW is calculated by dividing the flux below the emission line of Hα by the flux of the continuum. Both sources of Hα EW for Kiman et al. (2019; West et al. 2011; Schmidt et al. 2015) used the same definition for the emission line: 6557.61–6571.61 Å, and the surrounding continuum: 6530–6555 and 6575–6600 Å. Both West et al. (2011) and Schmidt et al. (2015) measured the Hα EW from spectra with R ~ 1800 resolution. Our literature search sample, however, contains objects with measurements of Hα EW from different spectral resolutions (shown in Table 2) that were calculated with slightly different definitions of the line and the continuum. This diversity of approaches and results could cause inconsistencies in our analysis. To account for the differences between Hα EW measurements, we followed a procedure similar to the one described in Newton et al. (2017). We only used the Hα EW from catalogs that were compatible with the Kiman et al. (2019) sample, as that is the largest component of our literature search sample (see Section 2.1). We considered a given catalog compatible if it had at least one star in common and if at least 90% of the stars in common had a difference in Hα EW smaller than 3 Å (|ΔHα EW| < 3 Å) with the measurement in Kiman et al. (2019). We chose 3 Å as the limit because this is the typical Hα variability for M4 – M5 identified by Lee et al. (2010) in a spectroscopic survey of 43 M dwarfs in the range M3.5 – M8.5. This cut assumes that 90% of the M dwarfs have small variability. We note that this might bias against variable >M5 dwarfs because variability increases for later types (Lee et al. 2010).

We defined the criterion described above as first-order compatibility, and it is indicated with a 1 in the column “OC” of Table 2. We could only find three catalogs from the literature search that had overlapping stars with Kiman et al. (2019): Douglas et al. (2014), Fang et al. (2018), and Reiners & Basri (2010). Therefore we decided to iterate upon our method and search for further studies compatible with these three catalogs to increase the number of stars we consider compatible. We
repeated the procedure described above to find what we defined as second-order compatibility catalogs. These second-order compatibility catalogs do not have stars in common with Kiman et al. (2019), but they do have stars in common with at least one of the order 1 catalogs.

All in all, we found 24,202 unique M dwarfs (99.6% of the sample) with Hα EW measurements that were either in Kiman et al. (2019, order 0) or first- or second-order compatible, meaning that we can use them together to calibrate the age–activity relation. We excluded the 128 remaining M dwarfs from our analysis.

### 2.3. Removing Potentially Accreting M Dwarfs

To characterize the age–activity relation, we are interested in chromospheric Hα emission, but this spectral line could in some systems result from accretion. To distinguish between the two types of emission, we used an empirical criterion that depends on the star’s Hα EW and spectral type, developed by White & Basri (2003) based on a sample of low-mass T Tauri stars. They proposed that a T Tauri star is classical, meaning accreting, if $\text{H} \alpha \text{ EW} \gtrsim 10 \text{ Å}$ for K7–M2.5 stars, $\text{H} \alpha \text{ EW} \gtrsim 20 \text{ Å}$ for M3–M5.5, and $\text{H} \alpha \text{ EW} \gtrsim 40 \text{ Å}$ for M6–M7.5 stars.

Based on the White & Basri (2003) criterion, we removed 45 stars that are Hα outliers from our analysis because they are possibly accreting. It should also be noted that by using only Hα EW to discard possible accretors, we are also removing Hα EW outliers such as nonaccreting stars whose measurement of Hα was taken during a flare. In Table 3 we list the Hα EW outliers that are possibly accreting, identified in this study with their 2MASS name, spectral type, the Hα EW, and $\Delta \text{H} \alpha \text{ EW}$ above the limit defined by White & Basri (2003). Given that the criteria only extend to M7.5, we did not remove any later spectral types according to their Hα EW. Therefore we are likely to have some contamination from accreting later spectral types.

### 3. Identifying M Dwarfs in Young Associations and Comoving with White Dwarfs

#### 3.1. Identifying Young Association Members

As mentioned in Section 2.1, we complemented Kiman et al. (2019) with M dwarfs that were classified as members of young associations by previous studies and/or had Hα EW measurements. However, most of these studies were completed prior to the release of Gaia DR2, which provided kinematics of an unprecedented quality.

In light of the new astrometric improvement of the Gaia DR2 survey, we decided to re-assess the likelihood of membership for each source and/or identify new members. To obtain proper motions and parallaxes for our literature search sample, we used TOPCAT (Taylor 2005) and a 2″ radius for a match with Gaia DR2 objects. We found 97% (86,918 out of the original 89,270 sources) of our literature search sample in Gaia DR2. As mentioned in Section 2.1, we applied the quality cuts described in Kiman et al. (2019) to obtain the best astrometric and photometric data and to remove potential binaries, and we were left with 27,201 M dwarfs. To look for mismatches, we used the 726 M dwarfs in our sample with duplicated measurements of Hα EW (see Section 2.1) and compared their Gaia source id. All the duplicated stars had the same Gaia source id, except for 6 stars that we think are potentially unresolved M dwarf binaries because after visually inspecting them, we found that there was only one star with two Gaia sources in the image. These 6 stars were removed from our analysis.

To confirm or identify members of young associations from our literature search sample, we used the BANYAN $\Sigma$ Bayesian membership classification algorithm (Gagné et al. 2018).13 BANYAN $\Sigma$ models young associations with a multivariate Gaussian density. This Gaussian has a total of six dimensions: three galactic positions (XYZ), and three space velocities (UVW). BANYAN $\Sigma$ also models the galactic field within 300 pc by combining 10 multivariate Gaussians. To calculate the probability of a star belonging to a young association or the field, BANYAN $\Sigma$ compares observables such as position and proper motion to the multivariate Gaussian model in a Bayesian classification likelihood, and marginalizes over radial velocities and distances when they are not available. The marginalization integrals are solved with an analytical solution, making the code more precise and efficient. In total, 27 associations are modeled in BANYAN $\Sigma$ within 150 pc. A summary of the associations in BANYAN $\Sigma$ is provided in Table 4.

Using BANYAN $\Sigma$, we calculated the probability that any given M dwarf belongs to a known association according to its position, proper motion, parallax, and radial velocity when available from Gaia DR2. We used this code to analyze the 24,166 single, compatible, not accreting stars in our sample (see Section 2).

To remove as many false positives as possible without losing true positives, we used a 90% cutoff in the membership probability output by BANYAN $\Sigma$, as suggested by Gagné et al. (2018). In total, we found 871 M dwarfs, which yielded a 90% probability in a known young association. The remaining 23,274 stars were rejected as young association members by our cut and/or have a high probability (>90%) to be field stars according to BANYAN. In addition, 21 objects were removed because they were rejected as young association members by Gagné et al. (2018). These objects were rejected mostly

---

13 The IDL version is available at https://github.com/jgagneastro/banyan_sigma_idl. The Python version is also available at https://github.com/jgagneastro/banyan_sigma, and the web portal is available at http://www.exoplanetes.umontreal.ca/banyan/banyansigma.php.
because their literature radial velocity was inconsistent with that of the group.

Based on experience with kinematics and lithium abundances, we expect an average contamination from false members below 10% (Gagné et al. 2018). In Appendix A we show the color–magnitude diagrams for each of the young associations with all of the objects used in this study as members. We concluded that we cannot discard any objects with the color–magnitude diagrams. The distribution of members per young association is shown in Figure 1 and Table 4. We found that Praesepe (∼650 Myr, 251 sources) had the highest yield of objects from our sample, followed by Upper Scorpionis (∼10 Myr, 167 sources), the Pleiades cluster (∼112 Myr, 106 sources), and Tucana–Horologium (∼45 Myr, 97 sources). Therefore we compiled a significant number of stars covering a range of ages that allows us to calibrate the age–activity relation for ages <1 Gyr.

From the 871 young association members in this work, we found that 708 have the same original membership assigned in the literature, 17 had their moving group membership revised, and 167 were not identified as members in our literature search. From the 184 “new” candidate members or members that changed their membership, 2 were rejected as members using radial velocities from the literature, and 175 have previously been identified as young association members by studies not collected in this work, i.e., studies where Hα measurements were not used (Röser et al. 2011; Gagné & Faherty 2018; Gagné et al. 2018; Galli et al. 2018; Goldman et al. 2018; Luhman et al. 2018).

| Association | Short name | Age (Myr) | Age References | Total Members | New Members |
|-------------|------------|-----------|----------------|---------------|-------------|
| Taurus      | TAU        | 1.5 ± 0.5 | 1              | 3             | ...         |
| ρ Ophiuchi  | ROPH       | <2        | 2              | ...           | ...         |
| ε Chamaeleontis | EPSC | 3.7 ± 4.6 | 3              | 9             | 1           |
| Corona Australis | CRA | 4–5       | 4              | ...           | ...         |
| TW Hya      | TWA        | 10.0 ± 3.0| 5              | 10            | ...         |
| Upper Scorpius | USCO | 10.0 ± 3.0| 6              | 167           | 1           |
| 118 Tau     | 118TAU     | ∼10       | 7              | ...           | ...         |
| Upper CrA   | UCRA       | ∼10       | 8              | 1             | ...         |
| η Chamaeleontis | ETAC | 11.0 ± 3.0| 5              | 1             | ...         |
| Lower Centaurus Crucis | LCC | 15.0 ± 3.0| 6              | 20            | 1           |
| Upper Centaurus Lupus | UCL | 16.0 ± 2.0| 6              | 4             | 2           |
| 32 Orionis  | THOR       | 22 ± 4    | 5              | ...           | ...         |
| β Pictoris  | βPMG       | 24.0 ± 3.0| 5              | 54            | 1           |
| Octans      | OCT        | 35.0 ± 5.0| 3              | 1             | ...         |
| Argus       | ARG        | 40–50     | 9              | 1             | ...         |
| Columba     | COL        | 42.0 ± 6.0| 5              | 12            | ...         |
| Carina      | CAR        | 45.0 ± 11.0| 5             | 6             | ...         |
| Tucana–Horologium association | THA | 45.0 ± 4.0| 5 | 97 | ... |
| Platais 8   | PL8        | ~60       | 10             | ...           | ...         |
| Pleiades cluster | PLE | 112 ± 5   | 11             | 106           | ...         |
| AB Doradus  | ABDMG      | 149.0 ± 51.0| 5 | 36 | 1 |
| Carina-Near | CARN | 200.0 ± 50.0| 12 | 3 | ... |
| core of the Ursa Major cluster | UMA | 414.0 ± 23.0| 13 | 1 | ... |
| χ¹ For      | XFOR       | ~500      | 14             | 14            | ...         |
| Coma Berenices | CBER | 562.0 ± 98.0| 15 | 9 | ... |
| Praesepe cluster | PRA | 650.0 ± 50.0| 16 | 251 | ... |
| Hyades cluster | HYA | 750.0 ± 100.0| 17 | 79 | ... |

Notes.  
1. Kenyon & Hartmann (1995), (2) Wilking et al. (2008), (3) Murphy & Lawson (2015), (4) Gennaro et al. (2012), (5) Bell et al. (2015), (6) Pecaut & Mamajek (2016), (7) Mamajek (2016), (8) Gagné et al. (2018), (9) Zuckerman (2019), (10) Platais et al. (1998), (11) Dahm (2015), (12) Zuckerman et al. (2006), (13) Jones et al. (2015), (14) Pohln & Paunzen (2010), (15) Silaj & Landstreet (2014), (16) Douglas et al. (2019); Gao (2019), (17) Brandt & Huang (2015).

2. Total number of stars with Hα compatible (see Section 2.2).

3. Praesepe is not included in the current public version of Banyan Σ (v1.2, 2018 September 6).

Figure 1. Membership distribution for M dwarfs in our sample, with young associations ordered by age. We include a reference at the top of the figure for the age of each association. Repeated measurements are not included in the total number of stars per association. References for each association are listed in Table 4.
Rebull et al. (2018). The remaining 7 M dwarfs are new candidate members of the young associations identified in this study. In particular, 2MASS J12323103-7255068 was called a member of LCC by Goldman et al. (2018), which we revised to be a member of EPSC. These stars are summarized in Table 4 and listed in Table 5.

As a further check on the membership probabilities for the new candidate members (or those that changed membership group), we compared their position in the Gaia color–magnitude diagram to that of empirical sequences based on bona fide members of young association of different ages (Gagné et al. 2020), and members of each association (Gagné et al. 2018). To compare an individual star’s position in a color–magnitude diagram, it is important to evaluate the extinction due to interstellar dust. We used the extinction maps of STructuring by Inversion of the Local InterStellar Medium (STILISM; Lallement et al. 2014; Capitanio et al. 2017; Lallement et al. 2018)14 and the method of Gagné et al. (2020) to calculate dereddened Gaia DR2 G- and G RP-band magnitudes. In summary, a template spectrum of the appropriate spectral type is used to calculate the effect of a typical interstellar dust extinction curve on the full Gaia bandpasses and stellar spectra, a step that is required because the Gaia bandpasses are particularly wide. Interstellar extinction will thus typically move M dwarfs down along isochrones (redder colors and fainter magnitudes) in a Gaia absolute G versus G − G RP color–magnitude diagram, but it will move the high-mass stars horizontally to redder colors, and across distinct isochrones. The position in the color–magnitude diagram of our new candidate members is shown in Figure 2 and is compared to empirical sequences based on bona fide members of young associations of different ages (Gagné et al. 2020) and members of Upper Scorpius, Lower Centaurus Crux, Upper Centaurus Lupus, β Pictoris, and AB Doradus (Gagné et al. 2018). We performed a visual inspection of all the high-probability members, and found that all the stars lie around the corresponding age sequences and/or within the scatter of the groups. This comparison corroborates their BANYAN Σ membership classifications when the scatter of the group is taken into account. However, more study is needed before they are considered as members. The summary of the catalogs we used to compile all these M-dwarf age calibrators with Hα EW measurements with a >90% probability of membership in a young association is given in Table 2.

### Table 5

| 2MASS Name          | SpT | Young Association | Source                        |
|---------------------|-----|-------------------|-------------------------------|
| J06511842−2154268   | M1.5| ABDMG             | Riaz et al. (2006)            |
| J03270844+2212382    | M4.5| BPMG              | Jeffers et al. (2018)         |
| J12323103−7255068    | M3.5| EPSC              | Riaz et al. (2006)            |
| J12554838−5133385    | M2.0| LCC               | Riaz et al. (2006)            |
| J15264071−6110559    | M3.0| UCL               | Riaz et al. (2006)            |
| J16544682−3502540    | M4.0| UCL               | Riaz et al. (2006)            |
| J16040453−2346377    | M4.0| USCO              | Slesnick et al. (2006)        |

#### 3.2. Identifying and Age-dating Comovers with White Dwarfs

With BANYAN Σ, we can cover age calibrators up to ~750 Myr. For older ages we turned to white dwarfs as chronometers to identify older age calibrators. White dwarf cooling models and model atmospheres are robustly developed to estimate precise and reliable cooling ages and masses (Fontaine et al. 2001). These models can be used to calculate total ages with a 10%–20% precision (Fouesneau et al. 2018) and as old as 12 Gyr (Cummings et al. 2018). Using comoving white dwarf systems as age calibrators therefore greatly expands the range used for grounding the age–activity relation.

The summary of the catalogs in which we found M dwarfs with a white dwarf comover that served as age calibrators is given in Table 2. To find M dwarfs that are comoving with white dwarfs, we cross-matched our literature search sample with the white dwarf catalog of Gentile Fusillo et al. (2019) using a 10’ radius. Gentile Fusillo et al. (2019) used a catalog of spectroscopically identified white dwarfs from the Sloan Digital Sky Survey (York et al. 2000) to define cuts to select 486,641 white dwarfs from the Gaia DR2 color–magnitude diagram. In our study we only used the 260,000 high-confidence white dwarf candidates (P _WD > 0.75), as suggested by Gentile Fusillo et al. (2019).

To find M dwarfs that are comoving with a white dwarf, we used the 23,274 sources that had good Gaia data, but were rejected as young association members and/or have a high probability (>90%) to be field stars according to BANYAN Σ (Section 3.1). We did not look for white dwarfs that are comoving with M dwarf members of young associations because the age of the moving group is better constrained than the estimation of the white dwarf age (see Section 1). Additionally, companion searches within young associations based solely on kinematics produces many false positives due to their high probability of chance alignment.

We considered an M dwarf and a white dwarf to be comoving if:

1. π wd /σ π wd > 4
2. π m /σ π m > 10
3. |μ WD , wd − μ WD , m | < 3 × (σ μ WD , wd + σ μ WD , m )
4. |μ WD , wd − μ WD , m | < 3 × (σ μ WD , wd + σ μ WD , m )
5. |π wd − π m | < 3 × (σ π wd + σ π m )

The cut on the signal-to-noise ratio for the white dwarf parallax (σ π wd /σ π wd ) is lower than for M dwarfs, as suggested by Gentile Fusillo et al. (2019), and the signal-to-noise ratio for M dwarfs (σ π m /σ π m ) follows the suggestions by Lindegren et al. (2018). For both components of the proper motion (μ WD, wd and μ WD, m) and the parallax (π), we required that the difference between the value for the white dwarf and the M dwarf in a pair was smaller than 3σ, where σ is the sum of the errors in each parameter. In total, we found 61 pairs with these criteria.

To remove false-positive companions, we calculated the probability of chance alignment for each M dwarf by reassigning the0 proper motions of all the white dwarfs in Gentile Fusillo et al. (2019) and repeating the search for comovers with the criteria described above, N = 1000 times. We then calculated the probability of chance alignment for each M dwarf as n rand /N, where n rand is the number of random comovers, and required it to be smaller than 0.01 to include a pair in our analysis. By adding this cut on probability of chance alignment, we remove pairs with several close-by white dwarfs, which makes a random match more likely. Out of the 61 pairs found, 22 had a probability of chance alignment higher than 0.01.

To calibrate the age–activity relation, wide dwarf-M dwarf pairs are key to assuming that both components
evolved as single stars without interacting. We estimated the physical separation between the pairs as $a = 1.22 \theta \times D$, where $a$ is the separation in au, $\theta$ is the angular separation, and $D$ is the distance in parsecs. We found that the closest pair is separated by $\sim 500$ au, therefore we can assume that the two stars in each pair evolved independently (Dhital et al. 2015; Skinner et al. 2017).

Once we identified the 39 M dwarf-white dwarf pairs, we used the open-source Python package available online, wdwarfdate (R. Kiman et al. 2021, in preparation)\(^\text{15}\), to estimate their age. wdwarfdate estimates ages of white dwarfs in a Bayesian framework from an effective temperature and a surface gravity. Twenty-one of the total number of pairs had effective temperature and surface gravity from Gentile Fusillo et al. (2019) and were in the ranges in which the models we use are valid. Using this information and cooling models (Bergeron et al. 1995, 2011; Fontaine et al. 2001; Holberg & Bergeron 2006; Kowalski & Saumon 2006; Tremblay et al. 2011; Blouin et al. 2018)\(^\text{16}\), we obtained the cooling ages and the masses of the white dwarfs. With a semiempirical initial-final mass relation (Cummings et al. 2018) and the masses of the white dwarfs, we obtained the masses of the progenitor stars, which were used with the MESA Isochrones (Paxton et al. 2011, 2013, 2015, 2018; Choi et al. 2016; Dotter 2016) to

\(^{15}\) https://wdwarfdate.readthedocs.io/en/latest/

\(^{16}\) http://www.astro.umontreal.ca/~bergeron/CoolingModels/
Table 6

| Gaia Source Id | White Dwarf | Total Age (Gyr) |
|----------------|-------------|----------------|
| 254356734628019712 | 25434722797040320 | 3.05±0.15 |
| 254403286155342080 | 254402458243877088 | 1.41±0.09 |
| 25694751549610368 | 2536960940812858760 | 2.57±0.04 |
| 2569659378956352 | 25367057206069304 | 1.94±0.03 |
| 326487155423918528 | 326487155423918784 | 1.71±0.03 |
| 4006695825601458816 | 4006671533266385792 | 2.07±0.04 |
| 4030722598505336192 | 4030722594210006784 | 2.06±0.03 |
| 7037471976591475483 | 70373438491279488 | 0.64±0.01 |
| 739097619303531776 | 739097619303531904 | 2.91±0.02 |
| 3898427744542897152 | 3898427744542897408 | 1.67±0.02 |
| 400695825601458816 | 4006671533266385792 | 2.5±0.11 |
| 392872492848850568 | 392872492512893299 | 1.27±0.07 |
| 1465165948332089472 | 1465165948332089600 | 1.94±0.09 |
| 161079879385356384 | 1610800721452287488 | 2.45±0.15 |
| 442463974212380800 | 4424639638053787776 | 3.66±0.03 |
| 132173856143758952 | 132173856727292184 | 4.87±0.06 |
| 132890768087155072 | 132890923620799904 | 4.61±0.18 |
| 4467448891397012992 | 4467448853280423296 | 4.35±0.23 |

4. Measurements and Unresolved Binaries

4.1. Calculating \( L_{\text{H}\alpha}/L_{\text{bol}} \) for the Age calibrators

The activity strength of M dwarfs is usually quantified with the ratio of the H\( \alpha \) luminosity to the bolometric luminosity \( L_{\text{H}\alpha}/L_{\text{bol}} \) (Hawley et al. 1996; West et al. 2008b; Schmidt et al. 2015). Using this fractional H\( \alpha \) luminosity removes the dependence on the continuum of the H\( \alpha \) EW and facilitates the comparison of stars of different effective temperatures. We empirically calibrated as a function of

4.2. Unresolved Binary Identification

We performed a search for known external factors that could increase the magnetic activity of the star, such as close binarity (Morgan et al. 2012; Skinner et al. 2017) and accretion disks outside the White & Basri (2003) criteria (see Section 2.3) between our age calibrators. We used the empirical sequences based on bona fide members for each young association (Gagné et al. 2020) to search for photometric binaries by identifying M dwarfs in the binary sequence, hence at most 0.75 brighter in absolute magnitude (\( M_G \)) for a given color (\( G - G_{\text{BP}} \)) than the value indicated by the model. We visually inspected each potential binary in the color–magnitude diagram of its respective young associations, and only selected stars for which we were able to confirm that they lived in the binary sequence. We only applied this method for stars with \( G - G_{\text{BP}} < 1.2 \) because the binary sequence is highly scattered for redder stars. We identified five potential binaries, which are indicated in the age calibrators sample in the column potential_binary with a 1. These stars were removed from the following analysis.

5. Activity Fraction

We used the young part of the sample of age calibrators, described in the previous section, to calculate the activity fraction as a function of color for M dwarfs younger than 1 Gyr and compared it with previous activity studies of field dwarfs. In this section we describe how we classified M dwarfs as active or inactive, and the resulting activity fraction.

5.1. Fitting the Inactive Sequence

Previous studies have identified what we define as the inactive sequence in this study, in H\( \alpha \) EW versus mass or effective temperature for M dwarfs (e.g., Stauffer & Hartmann 1986; López-Santiago et al. 2010; Newton et al. 2017; Fang et al. 2018). This inactive sequence is defined as the lower boundary of the H\( \alpha \) EW versus mass, color, or spectral type relation, and it shows an increase in H\( \alpha \) EW from higher to lower temperatures for redder stars.
lower masses (or redder colors). This increase in Hα EW is related to a decrease in the Hα absorption from the photosphere, meaning a decrease in photospheric luminosity (Stauffer & Hartmann 1986), and not to an increase in emission. We used Kiman et al. (2019) objects to establish the inactive sequence for Hα EW versus \((G - G_{\text{RP}})\), and with it, the active or inactive category. To establish the inactive sequence following Newton et al. (2017), we iterated a third-degree polynomial fit to stars with Hα EW < 1 Å 10 times. In each iteration we rejected the stars that had an Hα EW higher than the best fit. We defined the activity boundary as the best fit to the inactive sequence plus a small increment, \(\delta\):

\[
\text{Hα EW} = -2.39 \times (G - G_{\text{RP}})^3 + 2.84 \times (G - G_{\text{RP}})^2 + 3.63 \times (G - G_{\text{RP}}) - 4.22 + \delta,
\]

where \(\delta = 0.75 \text{ Å}\), and it was added to make our classification into active and inactive compatible with previous definitions (West et al. 2011; Schmidt et al. 2015). This limit is valid in the range \(0.8 < (G - G_{\text{RP}}) < 1.55\) (M0 ≤ SpT ≤ M7). We considered all the stars that have an Hα EW above the boundary to be active. All other objects were considered inactive. We show the activity boundary, the best fit to the inactive sequence, and our classification as active and inactive in Figure 3. As a comparison, we show the limit for active and inactive used by Schmidt et al. (2015). Among other cuts related to the signal-to-noise ratio, Schmidt et al. (2015) considered inactive stars as those with Hα EW < 0.75 Å. Their limit agrees with our definition, except for a small deviation for spectral types <M0 and >M6.

5.2. Calculating Active Fraction as a Function of Age

Using the definition of active and inactive described above, we calculated the active fraction in bins of the red Gaia DR2 color \((G - G_{\text{RP}})\) and studied its dependence on age. We used the histogram function available in the Python package \texttt{numpy} (Oliphant 2006; Van Der Walt et al. 2011) to define the bins in color because it is optimized for non-normal data. We repeated this calculation for the following age bins: (0–20), (20–60), (100–150), (500–700), and (700–1000) Myr. The results are shown in Figure 4, where we included a reference to the mean spectral type (SpT) for each color at the top of the figure. We also included the activity fraction for the sample from Kiman et al. (2019) in black, which is assumed to be primarily field stars, and it reproduces the results from previous studies (West et al. 2004, 2011; Schmidt et al. 2015). The errors for each point were calculated based on a binomial distribution as

\[
\sigma_f = (f \times (1-f))/n,
\]

where \(f\) and \(\sigma_f\) are the active fraction and uncertainty, and \(n\) is the number of stars in the bin.

By analyzing the active fraction as a function of age in Figure 4, we show that the active fraction of M dwarfs evolves with age. There is a clear difference in the evolution of the active fraction between early- (<M2) and mid-M dwarfs (M4 – M7). While the active fraction for early-M dwarfs decreases from 1 to almost 0 between 0 and 750 Myr, for mid-M dwarfs, the active fraction stays close to 1. This difference between early- and mid-M dwarfs agrees with previous studies, which showed that later-type M dwarfs stay active longer than earlier-type stars (West et al. 2004, 2011; Schmidt et al. 2015).

The active fraction for early-type M dwarfs in Figure 4 decreases progressively from 0 Myr to field-age dwarfs, while for mid spectral types (M4 ≤ SpT ≤ M7), it seems to decrease more abruptly from (700–1000) Myr (blue line) to field stars (black line). Note that the field active fraction represents a distribution of different ages. Therefore the difference between the bins (700–1000) Myr and field for mid-type M dwarfs could be indicating that late types stay active longer, and we do not have a high enough age resolution to distinguish the progressive decrease of the active fraction with age. This discrepancy might also indicate that the magnetic activity of mid-type M dwarfs decreases more abruptly than for early-types.

Both (500–700) and (700–1000) Myr age bins (the two blue lines) are statistically equivalent and present a transition period centered at M2, where the active fraction increases from 0 to 1, for \(1.0 < (G - G_{\text{RP}}) < 1.2\). Significantly, this transition is completed close to spectral type ~M3, the limit between partially and fully convective M dwarfs (Chabrier & Baraffe 1997). The shape of this transition for both bins could be affected by other physical effects that increase the magnetic activity of a star. For example, the active fraction could increase because of close companions of the stars, which increase their magnetic activity (e.g., Kraus et al. 2011; Morgan et al. 2012; Dhillon et al. 2015; Skinner et al. 2017). For the colors \(1.0 < (G - G_{\text{RP}}) < 1.1\), the fraction of active stars is 20%, which is close to the multiplicity fraction of M dwarfs of (23.9 ± 1.4%) at separations <50 au found by Winters et al. (2019). We searched the literature for references of binarity and we did not find known binaries for these stars. Also, our sample is not complete, so we cannot compare directly to the results in Winters et al. (2019). Follow up observations are necessary to distinguish if these stars are still active at ~700 Myr, or they have an unresolved binary keeping them active.

---

**Figure 3.** Classification into active and inactive M dwarfs. We fit the inactive sequence shown as a solid black line using the Kiman et al. (2019) sample and defined the boundary between active and inactive stars as the inactive sequence plus \(\delta\), where \(\delta = 0.75 \text{ Å}\), shown as the dashed black line. Typical error bars are indicated for the active and inactive stars to the left of the plot. As a comparison, we include the boundary used by Schmidt et al. (2015) as a dashed gray line. We show active stars in orange and inactive stars in blue, classified with our criteria.
6. Updated Age–Activity Relation for Active M Dwarfs

6.1. Characterizing Hα versus Age

We used our calibrators for Hα EW and $L_{\text{H\alpha}}/L_{\text{bol}}$ to study the activity strength as a function of age (Figures 5(a) and (b), respectively). We divided the calibrators into three panels according to their spectral type: M0 – M2, M3 – M6, and M7 – M9, which roughly correspond to early-type partially convective, mid-type fully convective, and ultracool fully convective M dwarfs, respectively. In the $L_{\alpha}/L_{\text{bol}}$ plots we only show active stars. Inactive stars have $L_{\text{H\alpha}}/L_{\text{bol}}$ with a too low signal-to-noise ratio to be significant (the gray area in Figure 5(a)).

There is a large spread of Hα EW between early-, mid-, and late-type M dwarfs, especially at the younger ages, shown in Figure 5(a). As indicated by previous studies (e.g., Stauffer & Hartmann 1986; West et al. 2011; Schmidt et al. 2015), Hα EW increases from early- to late-M dwarfs of the same age, which explains this effect, and it is removed when $L_{\text{H\alpha}}/L_{\text{bol}}$ is calculated, as can be seen in Figure 5(b).

We found fewer than 10 mid- and late-type old (>1 Gyr) active M dwarfs according to their Hα EW, and no early types. We could not identify any external factors related to these stars, such as a close binary, which would increase their magnetic activity. Therefore we consider them to be true active stars (see Section 4.2). The three youngest late-type M dwarfs in the $L_{\text{H\alpha}}/L_{\text{bol}}$ are not displayed in the Hα EW plot because their EW values are higher than 25 Å and thus are outside of the axis limit.

We also note that there are stars in the inactive region at all ages in Figure 5(a) (Hα EW < 0.75 Å, gray area), meaning that a small Hα EW does not necessarily indicate old age for an M dwarf. However, we do see an increase in the number of stars with low Hα EW in the inactive region as age increases.

To study the trends of activity strength with age, we calculated the median values, 25 and 75 percentile for a sliding window of width 0.8 in units of log$_{10}$(Age/yr) for both Hα EW and $L_{\text{H\alpha}}/L_{\text{bol}}$. The results are shown in Figures 6(a) and (b), respectively. The relation between Hα EW and age for early-M dwarfs (purple lines in Figure 6(a)) shows a gradual decline from approximately 5 to 0 Å in ~1 Gyr. For mid spectral types (M3 – M6, orange lines) we observe a progressive decrease of Hα EW with age until ~1 Gyr. After 1 Gyr, we observe a large decline in Hα ($\Delta$Hα EW ~ 4 Å). There are too few late-type dwarfs in our sample for us to be able to make a robust conclusion. However, we do observe a decline in the value of Hα EW with age.

$L_{\text{H\alpha}}/L_{\text{bol}}$ presents a similar decay of magnetic activity for early and mid types (purple and orange lines) for ages <1 Gyr in Figure 6(b). After this age, early-type M dwarfs are all inactive in our sample, while mid-type M dwarfs present a transition to a steeper decrease of the magnetic activity with age. However, we need more old M dwarfs with Hα measurements to conclude about the evolution of magnetic activity after 1 Gyr.

There is significant scatter both in Hα EW and $L_{\text{H\alpha}}/L_{\text{bol}}$ at each age bin, partially due to the intrinsic variability of Hα (Lee et al. 2010; Bell et al. 2012). To study the scatter in more detail, we analyzed the M dwarfs in our sample that have duplicate measurements of Hα EW. Some of these duplicated stars come from different studies of the same young association, which performed their own Hα EW measurements. We also noticed that the duplicated age calibrators are, on average, at a slightly shorter distance than non-duplicated age calibrators. This tendency may be due to these stars being more likely to be selected by studies given the better quality of the data. We see no such tendency with spectral type. Therefore we are confident that we can use these duplicated measurements to study Hα variability. Our sample of age calibrators contains 155 stars with 2–6 independent measurements of Hα EW, which are shown in the top panel of Figure 7, with the different measurements of Hα EW corresponding to the same star joined by a line. We also show the difference between the maximum and minimum value of Hα EW for each star in the bottom panel of Figure 7. We note that 94% of the M dwarfs in the sample have an intrinsic Hα variability <5 Å. By searching the literature for the stars with higher Hα EW, we found that most of the stars that have $\Delta$Hα EW ≥ 10 Å are known as variable stars (Kiraga 2012; Schmidt et al. 2015; Samuș et al. 2017). This analysis of the variability shows that our 3 Å cut to distinguish compatible measurements was conservative (see Section 2.2). We also note that there is a correlation between...
ΔHα EW and Hα EW measurements that agree with the results from Lee et al. (2010) and Bell et al. (2012).

6.2. Fitting the Age–Activity Relation

We fit the age–activity relation measured with $L_{\text{H} \alpha}/L_{\text{bol}}$ for all active age calibrators (856 stars, Tables 2 and 1) without binning by spectral type ranges, given that we lack enough information per bin. A broken power law has been used in several previous studies of the X-ray age–activity relation (e.g., Jackson et al. 2012; Booth et al. 2017) and for the rotation–activity relation (e.g., Delfosse et al. 1998; Douglas et al. 2014; Núñez et al. 2016; Newton et al. 2017) for cool dwarfs to model a saturation regime where $L_{\text{H} \alpha}/L_{\text{bol}}$ remains constant, followed by a power-law decay. Furthermore, West et al. (2008a) found that for M dwarfs, $L_{\text{H} \alpha}/L_{\text{bol}}$ remains constant for young ages and then decays. Therefore we decided to use a broken power law to fit the age–activity relation. See Appendix B for a comparison of the broken power law and polynomials of different degrees using the cross-validation method.

We performed an MCMC fit to the age–activity relation using emcee (Foreman-Mackey et al. 2013) to estimate the
The parameters of the broken power law and their uncertainties. The broken power law we fit to the relation was of the form

\[
\begin{align*}
\log \left( \frac{L_{\text{H} \alpha}}{L_{\text{bol}}} \right)_{\text{model}} &= \begin{cases} 
\alpha_1 \log t_0 + \beta_1, & t < t_0 \\
\alpha_2 \log t_0 + \beta_2, & t \geq t_0,
\end{cases}
\end{align*}
\]

where \( t \) is the age of the star. We used a Gaussian function as the likelihood and uniform priors on each parameter. As discussed before, the age–activity relation for H\( \alpha \) is scattered due in part to the intrinsic variability of this emission line. We included an additional parameter, \( \sigma_v \), to model the intrinsic variability of H\( \alpha \) assuming that the variability of \( \log (L_{\text{H} \alpha}/L_{\text{bol}}) \) is the same for all stars, in other words, that the H\( \alpha \) intrinsic variability is proportional to H\( \alpha \) EW (Lee et al. 2010; Bell et al. 2012). The resulting likelihood for our model is

\[
\log \mathcal{L} = -\frac{1}{2} \times \sum_i \left( \frac{\log \left( \frac{L_{\text{H} \alpha}}{L_{\text{bol}}} \right)_{\text{model}} - \log \left( \frac{L_{\text{H} \alpha}}{L_{\text{bol}}} \right)_{i}}{\sigma_{\log (L_{\text{H} \alpha}/L_{\text{bol}}))}^2 + \sigma_v^2 \right) \]

where we sum over each measurement \( i \) of \( L_{\text{H} \alpha}/L_{\text{bol}} \) and age.

To ensure that the MCMC had converged, we calculated the autocorrelation time (\( \tau_f \)) for our likelihood and sampled our posterior by performing 100 \( \tau_f \) steps to ensure \( \sim 100 \) independent samples.\(^{17}\)

We show the maximum likelihood of the parameters of the broken power law and the \( \sigma_v \) over the age calibrators in Figure 8, as well as 100 random samples from the posterior distributions of the broken power-law parameters. We show the full posterior distributions and the maximum likelihood values for each parameter in Figure 9. As discussed in Section 6.1, we found for \( \log (L_{\text{H} \alpha}/L_{\text{bol}}) \) a decrease in activity strength from 1 Myr to \( t_0 \sim 776 \) Myr with a power-law index of \( \alpha_1 = -0.11^{+0.02}_{-0.01} \), with a variability of \( \sigma_v = 0.22 \pm 0.01 \). For ages \( >776 \) Myr, the relation shows a decline in magnetic activity with a power-law index of \( \alpha_2 = -0.88^{+0.20}_{-0.25} \). However,

\(^{17}\)To calculate the autocorrelation time, we followed the tutorial in https://emcee.readthedocs.io/en/stable/tutorials/autocorr/.
we added a random shift to their ages to facilitate visualization. Our model includes the denser areas of points. However, we do not have enough information to fit the breaking point or the power-law decay of the older stars.

Figure 8. Age activity relation for $L_{\text{H}\alpha}/L_{\text{bol}}$ for M dwarfs. We fit the relation with a broken power law using an MCMC. We show as a black line the maximum likelihood fit and as a dashed black line the fit $\pm \sigma$, which models the H$\alpha$ variability. We also include 100 draws from the posterior distributions for the parameters of the fit in purple. The age calibrators are shown as black points, and we added a random shift to their ages to facilitate visualization. Our model fits most of the younger stars (<1 Gyr) well, and the range of variability includes the denser areas of points. However, we do not have enough information to fit the breaking point or the power-law decay of the older stars.

Figure 9. Posterior probabilities for each parameter of the broken power law we fit to the age–activity relation in Figure 8.

$t_0$ and the power-law index for old stars are based on fewer than 10 active old stars. Therefore these parameters are not well constrained with our data, as is shown by the purple line fits in Figure 8. We do not recommend using this fit for stars with ages >776 Myr. More data for older ages are needed to calibrate the decay. From Figure 8 we can conclude that there is a breaking point at which the magnetic activity starts to decline with a steeper slope according to H$\alpha$, and that it is at an age >776 Myr, as indicated by our $t_0$ parameter. As shown in Figure 5(b), the old active stars are of spectral type $\geq$M3, therefore this breaking point corresponds to late-type stars alone. We note that this age activity relation was obtained using only active stars. We will develop a model combining $L_{\text{H}\alpha}/L_{\text{bol}}$, the active fraction, color, and age in future work.

7. Comparison to Previous Age–Activity Relations

West et al. (2006) studied the H$\alpha$ age–activity relation by collecting a sample of M dwarfs with 3D positions, 3D kinematics, and H$\alpha$ EWs and luminosities. They found that $L_{\text{H}\alpha}/L_{\text{bol}}$ decreases with increasing vertical distance from the galactic plane and that the slope of the relation depends on the spectral type. As vertical distance is an age indicator such that older stars are located farther from the plane (Wielen 1977; Hanninen & Flynn 2002), their conclusion was that $L_{\text{H}\alpha}/L_{\text{bol}}$ decreases with increasing age. They also found that the active fraction of M dwarfs also decreases with vertical height. West et al. (2008b) used a one-dimensional model to simulate the dynamics of stars in the Galaxy and fit the relation between active fraction and vertical height. They found that the active lifetime of M dwarfs increases from 0.8 to 8 Gyr with spectral type (M0 to M7), meaning that later-type M dwarfs stay active longer than early-type ones. The results from our study of the active fraction as a function of color for different ages (Figure 4) agrees with the results from West et al. (2006) and other works that reported a similar analysis (e.g., Hawley et al. 1996; West et al. 2011; Schmidt et al. 2015). In addition, our age–activity relation (Figures 5, 6, and 8) qualitatively agrees with the results from West et al. (2008b).

West et al. (2008a) used a similar simulation as the we described above to find ages from the vertical height of the stars, and studied the relation between $L_{\text{H}\alpha}/L_{\text{bol}}$ and age for M2–M7 dwarfs. These relations are plotted as dot–dashed lines in Figure 10 for M2, M5, and M7 over the data for our age calibrators, which are divided according to spectral type range. We also included our results for the fit from Figure 8 as reference. We do not have enough M dwarf–white dwarf pairs with H$\alpha$ EW measurements to constrain the power-law index for ages >1 Gyr, so we did not include this part of the fit. We found that West et al. (2008a) overestimated the value of the activity strength for early-type M dwarfs and slightly underestimated it for late-type M dwarfs. Their relation also indicates that $L_{\text{H}\alpha}/L_{\text{bol}}$ remains constant for young ages up to the decline for all M dwarfs. Our fit describes the data better, and unlike West et al. (2008a), we found that $L_{\text{H}\alpha}/L_{\text{bol}}$ for early- and mid-type M dwarfs decreases progressively for ages <1 Gyr with a slope $\alpha_1 = -0.11^{+0.02}_{-0.01}$, as shown by the relation of the H$\alpha$ EW and age for each spectral type bin in Figure 6(a), the magnetic activity of old (>1 Gyr), mid-, and late-type M dwarfs seems to decline more rapidly than that of young stars, in agreement with West et al. (2008a). However, we found that early-type M dwarfs become progressively inactive, unlike their result, which indicates a steep decline.

The age–activity relation has been studied for other magnetic activity indicators. Stelzer et al. (2013) used a 90% complete sample of M dwarfs within 10 pc and found that the fluxes of H$\alpha$, X-ray, and UV are correlated. This correlation was expected given that the three parameters are indicators of magnetic activity. Therefore we also compared our results to X-ray and UV age–activity relations. Jackson et al. (2012) studied the age–activity relation using the X-ray luminosity for young F, G, and K dwarfs from known young associations (<1 Gyr) and found a saturated region for ages <100 Myr where the X-ray luminosity remains constant and then declines.
with a power-law index between $\alpha = -1.09 \pm 0.28$ and $-1.40 \pm 0.11$. Booth et al. (2017) also studied the dependence of X-ray luminosity for a sample of F, G, K, and M dwarfs with ages obtained from astroseismology or from white dwarf co-
movers, such that the stars had an age $>1$ Gyr. They found that the X-ray luminosity decreases with age with a power-law index of $\alpha = -2.8 \pm 0.72$. Instead of a saturated region where $L_{\text{X-ray}}$ remains constant, we found that magnetic activity for stars with ages $<1$ Gyr decreases with a small power-law index of $\alpha_1 = -0.01^{+0.02}_{-0.01}$ and for stars $>1$ Gyr of $\alpha_2 = -0.88^{+0.20}_{-0.25}$ (Figures 8 and 9). Although $\alpha_2$ is not well constrained by our model, our results seem to agree with those of Jackson et al. (2012) and Booth et al. (2017) in that the decrease in magnetic activity is faster for old than for young stars ($<1$ Gyr).

Schneider & Shkolnik (2018) studied a sample of M dwarfs from young associations ($<1$ Gyr) and compared it to field dwarfs to characterize the UV age–activity relation. They found that mid- to late-M dwarfs (0.08–0.35 $M_\odot$) remain actively throughout their lifetimes according to the UV flux density, with only a small decrease in magnetic activity from young to field ages. They also found that early-M dwarfs (0.35–0.6 $M_\odot$) have a much more significant decrease in magnetic activity over the same age range. This result agrees with our result for the evolution of the magnetic activity using $H_{\alpha}$. For the active fraction as a function of $(G - G_{RP})$ color for different age bins in Figure 4, we found that the active fraction of early-type M dwarfs decreases from 1 to almost zero for field dwarfs, while the active fraction for mid-type M dwarfs remains close to one for ages $<1$ Gyr and declines at an older age.

8. Conclusions

In this study, we analyzed the age dependence of the magnetic activity of M dwarfs from three complementary perspectives: (1) the dependence of the active fraction of spectral subtypes on age, (2) the dependence of $H_{\alpha}$ EW on age, and (3) the dependence of fractional $H_{\alpha}$ luminosity ($L_{H_{\alpha}}/L_{\text{bol}}$) on age. We compiled a sample of 892 compatible single M0 – M9 dwarfs (1121 in total, including repeated measurements and not compatible measurements) to serve as age calibrators, based on 89,270 M dwarfs with $H_{\alpha}$ EW measurements collected from the literature, focusing on M dwarf members of young associations or those that are comoving with a white dwarf. We cross-matched our sample with Gaia DR2 to obtain proper motions and parallaxes and found that 97% of our sample were in Gaia DR2. From this sample, we identified 871 M dwarf members of known young associations ($<1$ Gyr) using Gaia DR2 kinematics and parallaxes, and BANYAN $\Sigma$ (Gagné et al. 2018), as well as 21 M dwarfs that are comoving with a white dwarf from Gentile Fusillo et al. (2019). The age for M dwarf members of young associations was obtained from the estimated age of their association. For M dwarfs that are comoving with a white dwarf, the age was calculated with the Python package $\text{wdwarfdate}$ (R. Kiman et al. 2021, in preparation), which is available online.\(^{18}\) We have made the code used in this work available on Zenodo (Kiman 2021) and GitHub.\(^{19}\)

We present the results of our analysis as follows:

1. Of the 871 identified members of young associations in this study, 7 are new candidate members (Table 5).
2. We studied the variability of $H_{\alpha}$ at young ages for 155 M dwarfs with 2–6 independent $H_{\alpha}$ EW measurements. We found that 94% of the sample have a $\Delta H_{\alpha} \leq 5 \AA$ for ages $>1$ Gyr, where $\Delta H_{\alpha}$ is the difference between the maximum and minimum value of $H_{\alpha}$ EW (see Figure 7).
3. We confirmed that both $H_{\alpha}$ EW and $L_{H_{\alpha}}/L_{\text{bol}}$ decrease with age for spectral types M0 – M9. We lack a large enough sample to determine a precise trend in late-M dwarfs ($>M7$). Kiman et al. (2019) found a dependence of $L_{H_{\alpha}}/L_{\text{bol}}$ on vertical action dispersion, which is also a proxy for age (Wielen 1977; Hänninen & Flynn 2002). Figure 20 of Kiman et al. (2019) shows that $\log_{10}(L_{H_{\alpha}}/L_{\text{bol}})$ decreases from $-3.5$ to $-5$ for both mid (M5 $\leq$ SpT $\leq$ M8) and late spectral types (SpT $\geq$ M8), which agrees with the dependence of $L_{H_{\alpha}}/L_{\text{bol}}$ on age that we found for M dwarfs that are comoving with white dwarfs (see Figure 5(b)). This result indicates that mid-type M dwarfs ($\sim$M3 – M6) have a similar $H_{\alpha}$ age–activity relation to ultracool dwarfs ($>M6$).
4. We classified our age calibrators as active or inactive according to their $H_{\alpha}$ EW. Using this classification, we calculated the active fraction per color bin. We confirmed that the active fraction increases with color, which is a proxy for decreasing mass, from M0 – M7, in agreement

\(^{18}\)https://wdwarfdate.readthedocs.io/en/latest/

\(^{19}\)https://github.com/rkiman/M-dwarfs-Age-Activity-Relation
with West et al. (2004) and Schmidt et al. (2015). Moreover, by calculating the active fraction per color per age bin, we found that the active fraction varies with age according to spectral type: the active fraction of early M dwarfs (<M3) decreases gradually from 1 to close to 0 between 0 and 750 Myr, while later types stay active longer, such that their active fraction stays close to unity for ages <1 Gyr (see Figure 4).

5. We found that the active fraction for early-type M dwarfs in the age-bin 700–1000 Myr is close to the field value (>1 Gyr), while mid-types have an active fraction close to unity in the age-bin 700–1000 Myr and 0.6 for the field. The difference in active fraction between early and mid-types after 1 Gyr could be indicating that late types stay active longer, and we do not have a high enough age resolution to distinguish the progressive decrease of the active fraction with age. This discrepancy also could be indicating that the magnetic activity of mid-type M dwarfs decreases rapidly after 1 Gyr (see Figure 4).

6. By comparing Hα EW and LHα/Lbol as a function of age, we found that the magnetic activity strength of early- and mid-type M dwarfs (<M7) gradually decreases during the first Gyr of their lives. After ~1 Gyr, early- and mid-types seem to behave differently. We found only two early -M dwarfs (<M3), which are both inactive and continue the trend of a gradual decrease of magnetic activity. For mid-type M dwarfs we found 14 old stars, 11 of which are inactive and present a large decline in Hα (ΔHα EW ~ 4 Å), which seems to indicate that the magnetic activity of mid-type M dwarfs decreases rapidly after ~1 Gyr. However, higher numbers of old stars (>1 Gyr) are needed to make a robust conclusion.

7. We found that the power-law index for the relation between LHα/Lbol and age—using all spectral types to fit the data—is α0 = −0.11±0.02 for ages <776 Myr. For older ages, we only have LHα/Lbol measurements for spectral types ≥M3 (the early types that were found are inactive). We found a power-law index of α2 = −0.88±0.20 for ages ≥776 Myr, but it is poorly constrained because it was fit on a sample of <10 old active stars; hence we do not recommend using this relation for stars with ages of ≥776 Myr (see Figures 8 and 9). We conclude that spectral types >M3 show a sharp decrease in Hα at ages ≥776 Myr. More Hα EW measurements of M dwarfs that are comoving with white dwarfs are needed to fit the age–activity relation for older ages.

In this study we did not take metallicity into account to calibrate the age–activity relation. Previous studies have shown that the metallicity is a source of scatter for the relation between magnetic activity indicators and age: as the metallicity increases, the convection becomes more efficient, which enhances chromospheric activity (e.g., Lyra & De Mello 2005; Lorenzo-Oliveira et al. 2016). Metallicity should not affect the age relation obtained from young associations given than those used in this study have similar values (Malo et al. 2014b). While metallicity might affect the relation for older stars, we are not setting a strong constraint on the age relation for older stars, so it does not modify our conclusions.

This work represents a great advancement in the understanding of the magnetic activity and evolution of M dwarfs. In addition, this work is key for studying star-planet interactions, identifying habitable exoplanets, and identifying true planet signals with the radial velocity method, which can be affected when the host star is magnetically active (ex. Robertson et al. 2013). In future work, we plan to model the relation between Hα EW and age using the calibration from this study. We will use this model in a Bayesian algorithm to estimate ages of individual M dwarfs from their Hα EW combined with other age indicators to improve the precision and accuracy of M dwarf ages.

The authors would like to thank Evgenya Shkolnik and Amelia Bayo for helpful references of Hα EW measurements and Jeff Andrews, Alejandro Núñez, and Siyi Xu for great discussions. The authors would also like to thank John Bochanski for the helpful comments on the paper.

Support for this project was provided by a PSC-CUNY Award, jointly funded by The Professional Staff Congress and The City University of New York.

This material is based upon work supported by the National Science Foundation under grant No. 1614527.

This work has been supported by NASA K2 Guest Observer program under award 80NSSC19K0106.

This work was supported by the SDSS Faculty and Student Team (FAST) initiative.

Support for this work was provided by the William E Macaulay Honors College of The City University of New York.

Software: TOPCAT (Taylor 2005); emcee (Foreman-Mackey et al. 2013); scipy (Virtanen et al. 2020); numpy (Oliphant 2006; Van Der Walt et al. 2011); matplotlib (Hunter 2007); Astropy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018); wdwarfdate (R. Kiman et al. 2021, in preparation).

Appendix A

Color–Magnitude Diagrams of Young Association Members Used in This Study

In this section we compare the position in the Gaia color–magnitude diagram of the stars we used as members of young associations in this study, with the position of candidate members of each young association (Gagné et al. 2018), and empirical sequences based on candidate members of young associations of different ages (Gagné et al. 2020). The color–magnitude diagrams for each young association are shown in Figure 11. We conclude that the stars we used in this study as members are not discarded based on the color–magnitude diagrams: although some stars do not follow the corresponding age sequence, they present a similar scatter as the candidate members (light blue empty circles). More studies of these systems are needed before they are confirmed as members.
Figure 11. CMDs comparing stars we used as members of young associations in this study (red circles) with candidate members of each association (light blue empty circles; Gagné et al. 2018). We also show a sample of field stars from Gaia DR2 in black, and the empirical sequences based on bona fide members of young associations for the ages of 10–15, 23, 45, 110, and 600 Myr (Gagné et al. 2020). The position in the CMD does not discard any of stars we used in this study as members.
(g) Lower Centaurus Crux, $15.0 \pm 3.0$ Myr.

(h) Upper Centaurus Lupus, $16.0 \pm 2.0$ Myr.

(i) $\beta$ Pictoris, $24.0 \pm 3.0$ Myr.

(j) Octans, $35.0 \pm 5.0$ Myr.

(k) Argus, $40 - 50$ Myr.

(l) Columba, $42.0 \pm 6.0$ Myr.

Figure 11. (Continued.)
Figure 11. (Continued.)

(m) Carina, $45.0 \pm 11.0$ Myr.

(n) Tucana-Horologium association, $45.0 \pm 4.0$ Myr.

(o) Pleiades cluster, $112 \pm 5$ Myr.

(p) AB Doradus, $149.0 \pm 51.0$ Myr.

(q) Carina-Near, $200.0 \pm 50.0$ Myr.

(r) core of the Ursa Major cluster, $414.0 \pm 23.0$ Myr.

Figure 11. (Continued.)
Appendix B
Comparison Models for Fitting the Age–Activity Relation

Previous studies have used the broken power law to fit age–activity relations (see Section 6.2). As we are interested in the predictive power of our model, we tested the broken power law against polynomials of degrees 1 to 6 using a cross-validation method. In this method, we leave one of the calibration stars out and fit the rest with one of the models we wish to compare. Then we use the fitted model to predict the value of the left-out element, and we calculate how close the predicted value is to the true value. The total score for each model is defined as

$$\text{total score} = \sum_k \frac{(H\alpha \text{ EW}_k - f(t_k))^2}{\sigma_{H\alpha \text{ EW}_k}^2},$$

where $H\alpha \text{ EW}_k$ and $t_k$ are the equivalent width and the age of the excluded $k$-element, respectively, and $f$ represents the model being tested, so that $f(t_k)$ predicts the value of $H\alpha \text{ EW}$. The model with the lowest score predicts the new data best.

Applying the described cross-validation method with the scipy Python package (Virtanen et al. 2020), we found that a first-degree polynomial and a broken power law had the lowest cross-validation scores, indicating that these models can predict the ages based on $H\alpha$ better. Therefore we confirm the choice of a broken power law to fit the age–activity relation.

ORCID iDs
Rocio Kiman @ https://orcid.org/0000-0003-2102-3159
Jacqueline K. Faherty @ https://orcid.org/0000-0001-6251-0573
Kelle L. Cruz @ https://orcid.org/0000-0002-1821-0650
Jonathan Gagné @ https://orcid.org/0000-0002-2592-9612
Ruth Angus @ https://orcid.org/0000-0003-4540-5661
Sarah J. Schmidt @ https://orcid.org/0000-0002-7224-7702
Andrew W. Mann @ https://orcid.org/0000-0003-3654-1602
Daniella C. Bardalez Gagliuffi @ https://orcid.org/0000-0001-8170-7072
Emily Rice @ https://orcid.org/0000-0002-3252-5886
