Exploring the Age-dependent Properties of M and L Dwarfs Using Gaia and SDSS

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Abstract

We present a sample of 74,216 M and L dwarfs constructed from two existing catalogs of cool dwarfs spectroscopically identified in the Sloan Digital Sky Survey (SDSS). We cross-matched the SDSS catalog with the Gaia Collaboration to make them suitable for late-M and L dwarfs. We also provide relations between age and magnetic activity as a function of position on the color–magnitude diagram, finding that Hα magnetically active stars have, on average, redder colors and/or brighter magnitudes than inactive stars. This effect cannot be explained by youth alone and might indicate that active stars are magnetically inflated, binaries, and/or high metallicity. Moreover, we find that vertical velocity and vertical action dispersion are correlated with Hα emission, confirming that these two parameters are age indicators. We also find that stars below the main sequence have high tangential velocity, which is consistent with a low metallicity and old population of stars that belong to the halo or thick disk.

Key words: stars: activity – stars: kinematics and dynamics – stars: low-mass

Supporting material: FITS file

1. Introduction

The Milky Way is dominated in number by low-mass stars occupying the M and L spectral types (e.g., Gould et al. 1996; Bochanski et al. 2010). M dwarfs have a wide range of ages in the Milky Way because they have main-sequence lifetimes longer than the current age of the universe (e.g., Fagotto et al. 1994; Laughlin et al. 1997). This makes them an ideal population for studies of the structure, dynamics, and evolution of the stellar thin disk. Ages of field solar-type stars are typically obtained by three methods (Soderblom 2010): (1) empirical methods, such as activity–age relations (Mamajek & Hillenbrand 2008) and rotation period–age relations, called gyrochronology (Skumanich 1972; Barnes 2007; Angus et al. 2015; Meibom et al. 2015; Van Saders et al. 2016); (2) model-dependent methods, such as isochrone fitting (Edvardsson et al. 1993) and asteroseismology (Chaplin et al. 2014); and (3) statistical methods, such as kinematic age dating (Wielen 1977). Despite the availability of multiple methods, assigning accurate ages to M and L dwarfs in the field remains challenging. Because of their long main-sequence lifetimes, age-related parameters change slowly with time. Asteroseismological methods cannot yet be applied to M dwarfs as their acoustic oscillations have extremely small amplitudes (Rodríguez et al. 2016), and their isochronal stellar evolution models are not accurate, in part because of the difficulty associated with modeling fully convective interiors (Baraffe et al. 2015). Empirical and statistical methods are the best option to obtain ages for field M and L dwarfs.

Solar-type stars have a radiative core and a convective envelope that do not rotate as a rigid body. It is generally thought that, as a consequence of this differential rotation, a dynamo is generated at the interface of the two zones, which is responsible for the magnetic activity of the star (Parker 1955). When the magnetic field threads through the surface, it heats the chromosphere and the corona, generating collisionally induced atomic emission (including the Hα emission line) and X-ray emission, respectively. As a consequence, Hα and X-ray emission are measurable evidence of surface magnetism that can be used as magnetic activity indicators. The magnetic field is also partly responsible for the stellar magnetic wind, which dissipates angular momentum, slowing the rotation (and thus the differential rotation) of the star. As a result of this process, rotation, magnetic activity, and age are tightly related for solar-type stars (e.g., Skumanich 1972; Barry 1988; Soderblom et al. 1991; Mamajek & Hillenbrand 2008). Stars with masses <0.35 M⊙ (spectral type ∼M3) are fully convective (Chabrier & Baraffe 1997), so there is no interface with a radiative zone to produce a solar-type dynamo. Even though the mechanism to generate magnetic fields in fully convective stars is not yet understood, a strong correlation between rotation and magnetic activity is found for fully convective M dwarfs (e.g., Delfosse et al. 1998; Mohanty & Basri 2003; Reiners et al. 2012; West et al. 2015; Newton et al. 2017). Furthermore, several studies have extended the idea that magnetic activity decreases with age for late-M dwarfs (Eggen 1990; Fleming et al. 1995; West et al. 2006, 2008b; Riedel et al. 2017). This indicates that there is an empirical relation between age, rotation, and magnetic activity for M dwarfs that may extend to L dwarfs as well.

As they orbit the center of the Galaxy, stars gravitationally interact with giant molecular clouds and other passing stars, receiving a kinematic kick that alters their orbits. The increased eccentricity and inclination of the altered orbits causes the stars
to separate from the plane of the Galaxy as they age. This effect is generally quantified by the age–velocity relation (Wielens 1977; Hänninen & Flynn 2002), which indicates the velocity dispersion of a population of stars with a similar age, goes as the square root of its age \( \sigma = \sqrt{\mu} \). This relationship is particularly strong when examining the correlations between Galactic height or vertical velocity and age (e.g., Nordstrom et al. 2004; West et al. 2006, 2008b; Aumer et al. 2016; Yu & Liu 2018). This statistical method was used by several works to obtain kinematic ages of population of stars (e.g., Schmidt et al. 2007; Zapatero Osorio et al. 2007; Faherty et al. 2009; Reiners & Basri 2009). Thanks to large spectrophotometric surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) and astrometric surveys such as Gaia DR2 (Gaia Collaboration et al. 2016, 2018b), better results can be expected from statistical methods.

Our ultimate goal is to infer the ages of M and L dwarfs by combining different age indicators such as fractional H\(\alpha\) luminosity and vertical action dispersion. We began this process by compiling a sample of tens of thousands of spectroscopically identified M and L dwarfs, including colors, activity measurements, and kinematics, with sufficient precision to use vertical action dispersion as an age indicator. In this paper, we introduce the MLSDSS-GaiaDR2 sample, which includes H\(\alpha\) equivalent widths (H\(\alpha\) EWs), spectral types for M and L dwarfs, and radial velocities from two catalogs compiled from SDSS: the spectroscopic M dwarf catalog (West et al. 2011) and the the “BUD” catalog of Schmidt et al. (2015) and S. J. Schmidt et al. (2019, in preparation), as well as their vertical velocities and actions, calculated from Gaia DR2 proper motions, parallaxes, and positions.

This paper is laid out as follows. In Section 2, we describe the assembly of our M and L dwarf sample, including the process of cross-matching and combining data from different surveys, and the quality cuts we applied that remove incorrect matches and low-quality data. In Section 3, we fit relations to the Gaia colors/absolute magnitudes and spectral types of the M and L dwarfs in our catalog. In Section 4, we fit relations between the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) and SDSS absolute magnitudes and spectral types of stars in our sample. In Section 5, we briefly explore the relation between fractional H\(\alpha\) luminosity and tangential velocity and the position of the star in the Gaia color–magnitude diagram. We find that magnetically active stars have redder colors and/or brighter magnitudes than inactive stars and show that this effect cannot be explained only by youth and that radius inflation, metallicity, and binarity could be the causes. We also use color–magnitude position and tangential velocity to identify a possibly old halo or thick disk population of M dwarfs. In this section, we also discuss the relation between three age indicators in our catalog: H\(\alpha\) luminosity, vertical velocity, and vertical action. Finally, in Section 6 we summarize the work and our conclusions.

2. The MLSDSS-GaiaDR2 Sample

In this paper, we present the MLSDSS-GaiaDR2 sample of M and L dwarfs including spectral types, H\(\alpha\) measurements, survey photometry, and Galactic kinematics. The compilation of the MLSDSS-GaiaDR2 sample was accomplished in two parts: assembling the base sample, dubbed the “MLSDSS” sample, and then cross-matching it with the Gaia Data Release 2 (DR2; Gaia Collaboration et al. 2018b). The MLSDSS sample is based on data from the SDSS Data Releases 7, 10, and 12 (DR7; DR10; DR12; Abazajian et al. 2009; Ahn et al. 2014; Alam et al. 2015) and the SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS; Eisenstein et al. 2011; Dawson et al. 2013). The construction of the MLSDSS sample is described in Section 2.1 and the cross-match with Gaia DR2 is in Section 2.2. In Section 2.3, we describe the criteria we applied to the MLSDSS-GaiaDR2 sample to create a high-quality astrometric sample and the three resulting photometric subsamples.

2.1. Assembling the MLSDSS Sample

The MLSDSS sample is the combination of two catalogs of low-mass stars identified in SDSS: the DR7 spectroscopic M dwarf catalog (West et al. 2011) and the BOSS Ultracool dwarf “BUD” late-M and L dwarf catalog of Schmidt et al. (2015) and S. J. Schmidt et al. (2019, in preparation). The DR7 spectroscopic M dwarf catalog contains 70,841 M0–M9 dwarfs from SDSS DR7; these stars comprise the bulk of the MLSDSS sample. West et al. (2011) selected sources using color cuts designed to include all M dwarfs \((r - z > 0.42\) and \(i - z > 0.24\)) and then combined a spectral template matching code with visual inspection to classify stars with spectral types M0 to M9 according to their red-optical SDSS low-resolution \((R1800–2200)\) spectra. They also measured the H\(\alpha\) EW and fractional luminosity \((L_{H\alpha}/L_{bol})\) from the SDSS spectra and included the values with uncertainties for each star in their catalog. Finally, they give SDSS ugric photometry and 2MASS JHK\(_s\) photometry for the M dwarfs. The second component of the MLSDSS sample is the BUD catalog composed of 12,998 M7–L8 dwarfs. It includes 9623 M7–M9 dwarfs from the DR7 M dwarf catalog and an additional 484 L dwarfs from SDSS DR7 (Schmidt et al. 2010). The BUD catalog was also complemented with 2891 M7–L8 dwarfs selected as ancillary targets in the BOSS survey and released in SDSS DR10 (Schmidt et al. 2015) and DR12 (S. J. Schmidt et al. 2019, in preparation). The additional M7–M9 dwarfs were selected using the same color cuts of the West et al. (2011) catalog \((r - z > 0.42\) and \(i - z > 0.24\)); the L dwarfs were selected with \((i - z) > 1.44\). Schmidt et al. (2015) assigned spectral types for the L dwarfs and the additional M dwarfs. They adopted the spectral type classification assigned by West et al. (2011) for the rest of the M0–M8 dwarfs but reclassified all of the M9 dwarfs (S. J. Schmidt et al. 2019, in preparation). Schmidt et al. (2015) measured H\(\alpha\) EWs and \(L_{bol}/L_{H\alpha}\) for all objects in the BUD catalog. They also queried SDSS and 2MASS and reported new \(r, i, z, J, H,\) and \(K_s\) photometry. For the 9623 M7–M9 objects that are present in both the DR7 M dwarf and BUD catalogs, we adopted the photometry, H\(\alpha\) EW, and spectral type from BUD into the MLSDSS sample.

The spectral type distribution of the MLSDSS sample is shown in Figure 1. The sample is not complete and reflects the SDSS target selection and sensitivities. The spectroscopic targeting of SDSS avoided some of the most common M3/M4 stars, and the sample is also incomplete at later spectral types and fainter magnitudes because of the capabilities of the telescope and instrument.

Both the SDSS DR7 M dwarf spectroscopic catalog and the BUD catalog contain data relevant to kinematics and activity: an activity field (ACTHA) and proper motion and radial velocity.
estimates. We adopted these three values from the SDSS DR7 M dwarfs spectroscopic catalog for spectral types M0 to M6 and from the BUD catalog for spectral types M7 and later.

The ACTHA field mentioned above indicates whether the star is active or inactive (1 = active and 0 = inactive; described below). Both West et al. (2011) and Schmidt et al. (2015) classified stars as magnetically active or inactive according to the EW of the \( H\alpha \) emission line. Stars were considered active if they meet these four criteria: (1) the signal-to-noise ratio (S/N) per pixel in the region near \( H\alpha \) is greater than 3, (2) \( H\alpha \) EW > 0.75 Å, the detection threshold for SDSS spectra, (3) \( H\alpha \) EW is larger than its uncertainty, and (4) the peak height of \( H\alpha \) is greater than three times the noise level of the continuum region (measured by the standard deviation of the flux values). Stars that pass criterion (1) for S/N but do not pass the detection threshold are categorized as inactive. Stars that do not pass the first criterion were classified as neither active nor inactive, and stars that pass all criteria but the second were classified as weakly active and not included in this work.

Both the SDSS DR7 M dwarf spectroscopic catalog and the BUD catalog also include proper motions for the stars that were used as part of our cross-match procedure. The stars in the SDSS DR7 M dwarf catalog are all bright enough that proper motions were part of the (USNO-B; Munn et al. 2014) catalog, on the basis of SDSS and USNO-B positions, and have mean uncertainties of only 5 mas yr\(^{-1}\). The stars in the BUD sample, on the other hand, are too faint to be in the USNO-B, and their proper motions were calculated using positions from SDSS, 2MASS, and the Wide-Field Infrared Sky Explorer (WISE; Wright et al. 2010) by Schmidt et al. (S. J. Schmidt et al. 2019, in preparation) and have mean uncertainties of 20 mas yr\(^{-1}\).

Finally, both catalogs include radial velocities estimates with typical uncertainties of \( \sim 7 \) km s\(^{-1}\). These were measured via cross-correlation of the (R1800–2200) SDSS spectra to templates from Schmidt et al. (2014) and Bochanski et al. (2007).

When compiling the MLSDSS sample, we modified several fields from the two input catalogs to make them as consistent as possible with each other: the photometry quality flag (GOODPHOT_SDSS), the white dwarf-M Dwarf binary flag (WDM), and the photometry impacted by extinction.

The two input catalogs indicate good-quality photometry using different methods: the SDSS DR7 M dwarfs spectroscopic catalog assigned a single quality flag GOODPHOT_SDSS = 1 or 0 that depends on the quality of \( r \), \( i \), and \( z \)-band photometry (\( r \)-band extinction <0.05 mag, uncertainties <0.05 mag), while the BUD catalog has a flag for each band (using a combination of SDSS flags and uncertainty cuts to select good photometry, see Section 3.1 in Schmidt et al. (2015) for more details). We applied the first convention to the BUD stars, assigning them a GOODPHOT_SDSS = 1 value if the \( r \), \( i \), and \( z \)-band were all good.

Another difference between the two input catalogs is the WDM flag, which indicates whether the star is a white dwarf-M Dwarf binary (WDM = 1 is a binary and WDM = 0 is not). West et al. (2011) selected these pairs with the color cuts from Smolčić et al. (2004): \( u − g < 2 \), \( g − r > 0.3 \), \( r − i > 0.7 \), and \( σ_{u.g.r.i} < 0.1 \). The BUD catalog does not contain white dwarf-M Dwarf binaries (Schmidt et al. 2015) so we added a 0 in the WDM column for all of these stars.

Finally, West et al. (2011) corrected all five SDSS magnitudes for dust extinction using the Schlegel et al. (1998) maps. Schmidt et al. (2015) did not apply the correction to the magnitudes and instead included the extinction correction as a field in the BUD catalog. We applied the extinction correction for the stars in the BUD catalog so that all of the included SDSS photometry in the MLSDSS sample is corrected for extinction.

We found that some of the 2MASS photometry included in the DR7 M dwarf catalog was incorrect because of mismatches. This is demonstrated in Figure 2 where the \((z − J)\) versus \((i − z)\) color–color plot shows a significant scatter toward redder \((z − J)\) color, inconsistent with the \((i − z)\) colors and spectral types of the sample when compared to the median values and standard deviation for \((z − J)\) and \((i − z)\) colors of confirmed M and L dwarfs (West et al. 2011; Schmidt et al. 2015). The outliers do not have a low S/N \( J \)-band photometry and have good SDSS photometry (GOODPHOT_SDSS = 1). They are also more common among fainter, bluer stars that are
unlikely to be bright enough in 2MASS bands to have detections. It is therefore likely that the spurious colors are due to 2MASS mismatches with the SDSS source. We fit a line to the median values using the errors in \((z - J)\) as weights and removed the 2MASS information for the 1494 stars with \((z - J)\) colors more than 3\(\sigma\) above the fit, where \(\sigma\) is the mean propagated error on the \((z - J)\) color. These 1494 stars remain in the MLSDSS sample, just without 2MASS photometry.

The final MLSDSS sample includes 74,216 M and L dwarfs with spectral types, SDSS \(ugriz\) photometry, 2MASS \(JHKs\) photometry, H\(\alpha\) EW, and fractional luminosity \(L(\text{H}\alpha)/L_{\text{bol}}\), an activity classification, proper motions, and radial velocities.

### 2.2. Cross-match with Gaia DR2

We cross-matched the MLSDSS sample with Gaia DR2 to obtain precise proper motions and parallaxes. First, we propagated the positions from the SDSS epoch (ranging from 1999 to 2007) to the Gaia DR2 epoch (2015.5) using the proper motions in MLSDSS. Second, we queried the Gaia Archive\(^8\) and selected all the objects within a radius of 5\(^\prime\) of the 2015.5 position. We found that 98\% (73,003 stars) of MLSDSS stars have at least one match in Gaia DR2. Of these, 8269 have between two and five matches within a 5\(^\prime\) radius. To find a single best match, we propagated the position of each match back to the SDSS epoch using the Gaia DR2 proper motion and kept only the closest match between the Gaia position at the SDSS epoch and the SDSS position. We include a FITS table that contains the 73,003 matches in our sample as a supplementary file. In Table 1 we list the parameters in our sample and in the FITS table.

For this paper, we want a high-fidelity sample with a minimum of mismatches. We found that a 1\(^\prime\) separation between SDSS (R.A., decl.) and Gaia (R.A., decl.), propagated backward to the SDSS epoch using the proper motions from Gaia, provides a reasonable balance between sample size and cross-match reliability. A total of 67,573 stars (91\% of MLSDSS) have Gaia DR2 matches and a separation less than or equal to 1\(^\prime\). These are indicated in Table 1 with the GOODMATCH flag (GOODMATCH = 1 or 0). The analysis in this paper is based on these 67,573 objects with matches (GOODMATCH = 1) and we call this the “MLSDSS-GaiaDR2 sample.”

To check the goodness of the cross-matching, we examine a color–color plot of the MLSDSS-GaiaDR2 sample in Figure 3. Nearly all of the stars fall along the expected locus, and the \(\sim\)800 that fall off the locus are those with a high extinction correction to the SDSS magnitudes. The scatter in the color–color space is due to the lack of extinction correction applied to the \(G\) magnitude and does not indicate mismatches. Extinction corrections were not applied to the Gaia photometry in our sample because the extinction coefficients provided by the collaboration were calibrated for \(T_{\text{eff}} > 3500\) K and are not valid for low-mass stars (Gaia Collaboration et al. 2018a; Lindegren et al. 2018) are so conservative that they remove good-quality data for faint, red stars at the end of the main sequence. As a result, we modified the suggested cuts to adapt them for M and L dwarfs, the faintest stars in Gaia DR2. We describe these cuts in the following subsections.

#### 2.3. Quality Cuts

To ensure the cleanest possible sample of Gaia DR2 M and L dwarfs, we investigated optimal quality cuts for the photometric and astrometric data. The quality cuts in the Gaia Papers (e.g., Arenou et al. 2017; Evans et al. 2018;

\(^8\) http://gea.esac.esa.int/archive/)

Gaia Collaboration et al. 2018a; Lindegren et al. 2018) depend on factors such as the magnitude of the source, the number of observations per source, neighboring sources, and the type of source (Lindegren 2018). We describe below how we defined astrometric cuts for the MLSDSS-GaiaDR2 sample to obtain the best quality five-parameter solution. The astrometric cuts we used to clean the MLSDSS-GaiaDR2 sample are summarized in Table 2 and described below.

To ensure accurate parallaxes (mean uncertainty \(\sim\)0.2 mas), we applied the quality cut suggested by Lindegren et al. (2018): parallax\(\_\)over\_error > 10 (abbreviated as PE from here on). This cut conservatively removes poor astrometric solutions and reduces our sample by 60\%, removing 40,801 stars.

The number of Gaia observations included in each astrometric solution is an indicator of reliable astrometric data and is indicated in the visibility\_periods\_used field, abbreviated as VP from here on. As suggested in Gaia Collaboration et al. (2018a), we selected stars with VP \(> 8\) to restrict our sample to stars with enough observations to produce reliable astrometric solutions. This removes 8166 stars from the original MLSDSS-GaiaDR2 sample, leaving 24,589 stars when applied after the PE cut (see Table 2).

To remove poor astrometric solutions generated by binary stars and double stars, we also applied an astrometric cut based on the residual of the fit of the single star astrometric solution. The “unit weight error” (UWE) is a reduced \(\chi^2\) statistic and reflects the goodness of fit (Arenou et al. 2017; Lindegren et al. 2018). The square of the UWE is calculated as

\[
UWE^2 = \frac{\chi^2}{\nu} = \frac{\text{astrometric\_chi2\_al}}{\text{astrometric\_n\_good\_obs\_al} - 5},
\]

where \(\chi^2 = \text{astrometric\_chi2\_al}\) and \(\nu = N - 5\) is the degree of freedom, where \(N = \text{astrometric\_n\_good\_obs\_al}\) is the total number of good observations of the source. Lindegren et al. (2018) found that a good astrometric solution corresponds to UWE \(\sim 1\) and suggest a cut:

\[
\text{UWE} < 1.2 \times \max(1, \exp(-0.2(G - 19.5))).
\]

We show UWE as a function of \(G\) magnitude in Figure 4. The cut suggested by Lindegren et al. (2018), shown as a red dashed line, removes a high number of faint stars (\(G > 18\)) even though they have a good astrometric fit (UWE \(\sim 1\)). We wanted to retain faint stars for our sample of M and L dwarfs and future analysis, so we defined a new cut and increase the maximum UWE tolerance for faint stars from 1.2 to 1.68:

\[
\text{UWE} < 1.2 \times \max(1.4, \exp(-0.2(G - 19.5)))
\]

represented in a blue dashed–dotted line in Figure 4. This new cut matches the Lindegren et al. (2018) through \(G = 18\) and includes an extra 7132 stars with \(G > 18\) also having a good

### 2.3.1. Astrometric Quality Cuts

The quality of the five-parameter solution (\(ra, dec, pmra, pmdec,\) and \(\text{parallax}\)) given by Gaia DR2 depends on the Gaia Collaboration et al. (2018) quality cuts as follows.

- \(\text{GOODMATCH}\) = 1 indicates a good quality match.
- \(\text{GOODMATCH}\) = 0 indicates a good quality match with an extra check.

We used the quality cut suggested by Lindegren et al. (2018): \(\text{GOODMATCH} > 0\) (abbreviated as GM from here on). This cut conservatively removes poor quality solutions and reduces our sample by 60\%, removing 40,801 stars.

In addition, we used an astrometric quality cut based on the residuals of the fit of the single star astrometric solution. The “unit weight error” (UWE) is a reduced \(\chi^2\) statistic and reflects the goodness of fit (Arenou et al. 2017; Lindegren et al. 2018). The square of the UWE is calculated as

\[
UWE^2 = \frac{\chi^2}{\nu} = \frac{\text{astrometric\_chi2\_al}}{\text{astrometric\_n\_good\_obs\_al} - 5},
\]

where \(\chi^2 = \text{astrometric\_chi2\_al}\) and \(\nu = N - 5\) is the degree of freedom, where \(N = \text{astrometric\_n\_good\_obs\_al}\) is the total number of good observations of the source. Lindegren et al. (2018) found that a good astrometric solution corresponds to UWE \(\sim 1\) and suggest a cut:

\[
\text{UWE} < 1.2 \times \max(1, \exp(-0.2(G - 19.5))).
\]
| Name                        | Units      | Description                                                                 |
|-----------------------------|------------|----------------------------------------------------------------------------|
| MJD                         | day        | Modified julian date from SDSS                                              |
| PLATE                       |            | Plate number from SDSS                                                      |
| FIBER                       |            | Fiber number from SDSS                                                      |
| solution_id                 |            | Gaia DR2 Solution Identifier                                               |
| designation                 |            | Unique Gaia source designation (unique across all Data Releases)            |
| source_id                   |            | Unique Gaia source identifier (unique within DR2)                          |
| ref_epoch_gaia              | yr         | Reference epoch from Gaia DR2                                              |
| SPT                         |            | Spectral Type                                                               |
| RA                          | deg        | R.A. in Gaia DR2 epoch                                                      |
| RA_ERR                      | mas        | Standard error of R.A. in Gaia DR2                                          |
| DEC                         | deg        | Decl. in Gaia DR2 epoch                                                     |
| DEC_ERR                     | mas        | Standard error of decl. in Gaia DR2                                          |
| PMRA                        | mas yr⁻¹   | Proper motion in R.A. direction in Gaia DR2                                 |
| PMRA_ERR                    | 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_ERR                   | mas yr⁻¹   | Standard error of proper motion in decl. direction in Gaia DR2              |
| RV                          | km s⁻¹     | Radial velocity from MLSDSS                                                  |
| RV_ERR                      | km s⁻¹     | Radial velocity error from MLSDSS                                            |
| RA_SDSS                     | deg        | R.A. in SDSS photometric object                                              |
| DEC_SDSS                    | deg        | Decl. in SDSS photometric object                                             |
| PSFMAG                      | mag        | SDSS photometry ugriz-bands errors                                           |
| PSFMAG_ERR                  | mag        | Good photometry flag for SDSS riz-bands                                     |
| GOODPHOT_SDSS               |            | Extinction correction for ugriz-bands (A_u, A_g, A_r, A_i, A_a)              |
| EXTINCTION                  | mag        | Good proper motion flag for MLSDSS (1 = good proper motion)                  |
| PMRA_SDSS                   | mas yr⁻¹   | Proper motion in R.A. direction in MLSDSS                                    |
| PMRA_ERR_SDSS               | mas yr⁻¹   | Proper motion error in R.A. direction in MLSDSS                              |
| PMDEC_SDSS                  | mas yr⁻¹   | Proper motion in decl. direction in MLSDSS                                   |
| PMDEC_ERR_SDSS              | mas yr⁻¹   | Proper motion error in decl. direction in MLSDSS                             |
| MJD_2MASS                   | day        | Modified julian date from 2MASS                                             |
| RA_2MASS                    | deg        | R.A. in 2MASS                                                              |
| DEC_2MASS                   | deg        | Decl. in 2MASS                                                            |
| MAG_2MASS                   | mag        | 2MASS photometry JHK-bands                                                  |
| MAG_ERR_2MASS               | mag        | 2MASS photometry JHK-bands error                                            |
| ACTHA                       |            | Active flag (1 = active, 0 = inactive)                                      |
| EWHA                        | Å          | Equivalent width Hα                                                        |
| EWHA_ERR                    | Å          | Equivalent width Hβ error                                                  |
| LHALBOL                     |            | Fractional Hα luminosity                                                   |
| LHALBOL_ERR                 |            | Fractional Hβ luminosity error                                              |
| GOODWATCH                   |            | Good matches with Gaia DR2 (1 = good, 0 = probable mismatch)                |
| parallax                    | mas        | Parallax in Gaia DR2                                                        |
| astrometric_n_good_obs_al   |            | Number of good observations AL                                              |
| astrometric_chi2_al         |            | AL chi-square value                                                        |
| visibility_periods_used     |            | Number of visibility periods used in Astrometric solution                   |
| 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_flux_over_error | electron s⁻¹| G band mean flux divided by its error                                        |
| phot_g_mean_mag             | mag        | G band 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                                       |
| phot_bp_mean_flux_over_error| electron s⁻¹| Integrated G_Bp mean flux divided by its error                              |
| phot_bp_mean_mag            | mag        | Integrated G_Bp mean magnitude                                              |
| phot_rp_mean_flux           | electron s⁻¹| Integrated G_Rp mean flux                                                   |
| phot_rp_mean_flux_error     | electron s⁻¹| Error on the integrated G_Rp mean flux                                       |
| phot_rp_mean_flux_over_error| electron s⁻¹| Integrated G_Rp mean flux divided by its error                              |
| phot_rp_mean_mag            | mag        | Integrated G_Rp mean magnitude                                              |
| phot_rp_rp_excess_factor    |            | BP/RP excess factor                                                        |
| r_est                       | pc         | B-J estimated distance                                                      |
| r_lo                        | pc         | B-J lower bound on the confidence interval of the estimated distance        |
| r_hi                        | pc         | B-J upper bound on the confidence interval of the estimated distance        |
| r_len                       | pc         | B-J length scale used in the prior for the distance estimation              |
| v_R                         | km s⁻¹     | Mean radial component of the velocity                                       |
astrometric shows the number of stars left after applying that cut and the ones listed above it. Objects included in the astrometric sample are indicated with the of the column in the catalog and the criterion applied; correction to the astrometric supplementary fi

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Table 1
(Continued)

| Name                  | Units       | Description                                                                 |
|-----------------------|-------------|-----------------------------------------------------------------------------|
| V_R_ERR               | km s⁻¹      | Standard deviation of radial component of the velocity                      |
| V_T                   | km s⁻¹      | Mean tangential component of the velocity                                    |
| V_T_ERR               | km s⁻¹      | Standard deviation of tangential component of the velocity                  |
| V_Z                   | km s⁻¹      | Mean vertical component of the velocity                                     |
| V_Z_ERR               | km s⁻¹      | Standard deviation of vertical component of the velocity                    |
| J_Z                   | kpc km s⁻³  | Median vertical action                                                      |
| J_Z_16per             | kpc km s⁻³  | 16th percentile vertical action                                             |
| J_Z_64per             | kpc km s⁻³  | 64th percentile vertical action                                             |
| WDM                   |             | White dwarf-M dwarf binary flag (1 = binary, 0 = not binary)                 |
| astrometric_sample    |             | Astrometric subsample (1 = good astrometry, 0 = bad astrometry)             |
| photometric_sample_subg|             | Sub G subsample (1 = goodphot, 2 = outlier, 0 = badphot)                    |
| photometric_sample_subred|            | Sub Red subsample (1 = goodphot, 2 = outlier, 0 = badphot)                  |
| photometric_sample_submix|            | Sub Mix subsample (1 = goodphot, 2 = outlier, 0 = badphot)                  |

Note. Columns of the MLSDSS-GaiaDR2 sample of 74,216 M and L dwarfs, including the 73,003 matches with Gaia DR2. The table is available as a FITS table as a supplementary file. We include name of the columns, units, and a brief description.

Table 2
Summary of Astrometric Quality Cuts

| Flag | Cut                                                      | N Removed by Single Cut | N after Cumulative Cuts |
|------|----------------------------------------------------------|--------------------------|-------------------------|
| PE   | parallax_over_error > 10                                 | 40,801                   | 26,772                  |
| VP   | visibility_periods_used > 8                             | 8166                     | 24,589                  |
| UWE  | UWE < 1.2 × max(1.4, exp(−0.2(G − 19.5)))               | 2582                     | 23,842                  |

Note. Astrometric quality cuts applied to the MLSDSS-GaiaDR2 sample. The Flag column contains the name of the cut we use in this paper; Cut indicates the name of the column in the catalog and the criterion applied; N removed by Single Cut shows the number of stars removed by only that cut; and N after Cumulative cuts shows the number of stars left after applying that cut and the ones listed above it. Objects included in the astrometric sample are indicated with the flag astrometric_sample = 1.

Figure 3. (G − z) as a function of (r − z), with color-coding indicating the SDSS extinction value E(r − z) using the Schlegel et al. (1998) dust map. Each star shown is classified both as a good match between the MLSDSS sample and Gaia DR2 (GOODMATCH = 1) and has good SDSS photometry (GOODPHOT_SDSS = 1), as discussed in Section 2. The stars that fall along the color–color locus are easily verified as good matches. The stars that scatter toward redder (G − z) color are those with high extinction, indicating that their position off the color–color locus is likely due to the lack of extinction correction to the G band rather than mismatches in the catalog.

Figure 4. Unit weight error (UWE, defined in Equation (1)) as a function of G magnitude for the MLSDSS-GaiaDR2 sample color-coded with the density map. The Lindegren et al. (2018) cut (red dashed line) defined in Equation (2) removes most of the faintest stars (later Ms and Ls) with G ≥ 18 although they have UWE ∼ 1. We defined a new cut (blue dashed–dotted line) in Equation (3), that both removes stars with a bad astrometric solution and keeps the fainter stars. Stars retained after this cut are bellow the blue dashed–dotted line.

astrometric solution. Applying this cut removes 2582 stars from the original MLSDSS-GaiaDR2 sample, leaving 23,842 stars when applied after the PE and VP cuts (see Table 2).
Table 3  
Summary of Photometric Quality Cuts

| Subsample | Cut Expression | $N$ Stars |
|-----------|----------------|-----------|
| (1) Sub G | $\text{astrometric cuts}$  
  + $\text{phot}_{\text{bp}}_{\text{rp}}_{\text{excess factor}} < 1.3 + 0.06 \times (G_{\text{rp}} - G_{\text{bp}})^3$  
  only when $\text{phot}_{\text{bp}}_{\text{mean flux over error}} > 10$  
  (1) $+ \text{phot}_{\text{rp}}_{\text{mean flux over error}} > 10$  
  (2) $+ \text{phot}_{\text{bp}}_{\text{mean flux over error}} > 10$ | start = 23,842  
  22,706  
  ... |
| (2) Sub Red | (1) $+ \text{phot}_{\text{rp}}_{\text{mean flux over error}} > 10$ | 22,373 |
| (3) Sub Mix | (2) $+ \text{phot}_{\text{bp}}_{\text{mean flux over error}} > 10$ | 16,527 |

Note. Photometric quality cuts applied to the good astrometry sample (Section 2.3.1). The column Subsample indicates the name of the subsample used in this paper; the Cut expression indicates the name of the column in the catalog and the cuts that were made over that column; and $N$ Stars indicates the number of stars in each subsample. Objects in the subsamples are indicated with the flags, photometric_sample_subg = 1, photometric_sample_subred = 1, and photometric_sample_submix = 1, respectively.

Figure 5. Log of distance calculated by Bailer-Jones et al. (2018) as a function of the parallaxes measured in Gaia DR2. The MLSDSS-GaiaDR2 sample before our astrometric cuts (gray dots) is compared to the astrometric sample (black dots). The formula relating distance to parallax (solid red line) shows excellent agreement with the astrometric sample, validating the astrometric cuts applied to the MLSDSS-GaiaDR2 sample.

An alternative to this cut is described in the Technical Note by Lindegren (2018), where they define a new quantity called the renormalized UWE, or RUWE. Because the UWE is necessarily dependent on the color and magnitude of each star, the RUWE is designed to make a quality cut in the data that is relatively complete in color and magnitude. This is calculated by dividing UWE by a different normalization factor for each color and magnitude bin, which accounts for the fraction of good and bad data in each bin. We did not intend our sample to be complete in color and/or magnitude, and applying a cut on the RUWE removes $\sim 1000$ more stars than Equation (3), so we did not use RUWE in our quality cuts.

Once the three astrometric cuts summarized in Table 2 are applied, the MLSDSS-GaiaDR2 sample contains 23,842 stars with good astrometry. As a way of verifying our astrometric cuts, we cross-matched MLSDSS-GaiaDR2 with the Bailer-Jones et al. (2018) catalog that uses an inference procedure to account for the nonlinearity of $1/\pi$ for computing distances. If our astrometric cuts are valid, the distances calculated as $1/\pi$ with MLSDSS-GaiaDR2 should be the same as in the Bailer-Jones et al. (2018) catalog. We plot parallaxes from our sample against Bailer-Jones et al. (2018) distances in Figure 5 and confirm that the 23,842 parallaxes selected by our cuts follow the formula relating parallax and distance, $d = 10^3/\pi$, where $\pi$ is the parallax in milliarcseconds. This indicates that the quality of the astrometry in our final sample is excellent. Objects included in the astrometric sample are indicated with the flag astrometric_sample = 1 in the FITS file.

2.3.2. Photometric Quality Cuts for Gaia Bands

Given that the MLSDSS-GaiaDR2 sample contains predominantly faint and red stars, we also implemented several photometric cuts described below to ensure a sample without contamination and suitable for detailed color analysis. The cuts and the resulting subsamples are summarized in Table 3 and described below.

To ensure accurate Gaia photometry ($S/N > 10$), we applied cuts based on the $S/N$ for the flux in the three Gaia bands, $G$ ($[330, 1050]$ nm), $G_{\text{BP}}$ ($[330, 680]$ nm), and $G_{\text{RP}}$ ($[630, 1050]$ nm). We show the mean flux over error for these three bands in Figure 6. Gaia DR2 contains a column with the $S/N$ value for each band. Lindegren et al. (2018), in their Appendix C, suggest combining the cuts over $S/N$ for the blue and red band ($G_{\text{BP}}$ and $G_{\text{RP}}$ respectively): $\text{phot}_{\text{bp}}_{\text{mean flux over error}} > 10$ and $\text{phot}_{\text{rp}}_{\text{mean flux over error}} > 10$. The suggested cut for the blue $G$ band removes a significant number of stars from the MLSDSS-GaiaDR2 sample, while the same cut in the red band $G_{\text{RP}}$ only removes a handful of stars. This is expected because M and L dwarfs emit most of their flux at red wavelengths, so they are faint in the blue band. If we follow the suggestion made by Lindegren et al. (2018) and combine the cuts for the red and blue bands, we would remove 5846 stars that have $S/N < 10$ in $G_{\text{BP}}$, but $S/N \geq 10$ in $G_{\text{RP}}$. Furthermore, all the stars in the MLSDSS-GaiaDR2 sample have $S/N \geq 10$ in the $G$ band, as we show in the left panel in Figure 6. In particular, the 5846 stars that have low-quality blue photometry, $G_{\text{BP}}$ but high-quality red photometry, $G_{\text{RP}}$, have also good $G$ photometry. To maximize the number of stars available for each band with high $S/N$ photometry, we created three subsamples: in the first subsample (Sub G), we did not apply any $S/N$ cuts, only the $G$ photometry is necessarily $S/N \geq 10$; in the second subsample (Sub Red), we applied the $S/N$ cut in the red band ($G_{\text{RP}}$), resulting in good $G$ and $G_{\text{RP}}$ photometry; and in the third subsample (Sub Mix), we applied the $S/N$ cut to both the red and blue bands; therefore, it contains $S/N \geq 10$ photometry in $G$, $G_{\text{RP}}$, and $G_{\text{BP}}$ bands. The summary of these subsamples is presented in Table 3. Objects in the subsamples are indicated with the flags photometric_sample_subg = 1, photometric_sample_subred = 1, and photometric_sample_submix = 1, respectively.
The last source of photometric inaccuracy relevant to our sample is contamination generated by neighboring sources. As explained in Evans et al. (2018), the wavelength ranges of the \( G_{\text{RP}} \) and \( G_{\text{BP}} \) passbands overlap slightly. Therefore, the excess ratio defined as the flux ratio \( C = (I_{\text{RP}} + I_{\text{BP}})/I_G \), where \( I \) is the flux in the band indicated by the subindex, should be only slightly greater than 1. This quantity is indicated in Gaia DR2 in the column \( \text{phot}_\text{bp} \_\text{rp} \_\text{excess} \_\text{factor} \). Evans et al. (2018) and Arenou et al. (2017) suggest the following criteria to select stars with uncontaminated photometry:

\[
\text{phot}_\text{bp} \_\text{rp} \_\text{excess} \_\text{factor} < 1.3 + 0.06 \times (G_{\text{BP}} \_G_{\text{RP}})^2. \tag{4}
\]

The cut in Equation (4) selects the stars for which the excess factor \( C \) is close to 1. However, it depends on accurate \( G_{\text{BP}} \) photometry, which is not available for our faint, red stars. Accordingly, the excess factor increases for fainter stars as a function of the three bands. We examine this cut in the color-magnitude diagram shown in Figure 7. If we apply the cut suggested by Evans et al. (2018) to the MLSDSS-GaiaDR2 sample, it removes the spurious data shown in Figure 7 (left panel has no cuts and the middle panel has these cuts applied). However, it also removes stars at the bottom of the main sequence that we are interested in keeping for future analysis because they have good \( G \) and \( G_{\text{RP}} \) photometry. To reduce the number of high-quality stars being eliminated for conservative \( G_{\text{BP}} \) values that generate a large excess factor, we applied the cut on the excess factor in Equation (4) only when the blue photometry is good (\( \text{phot}_\text{bp} \_\text{mean} \_\text{flux} \_\text{over} \_\text{error} > 10 \), abbreviated as RBE cut hereafter). After adding this condition, the new cut to MLSDSS-GaiaDR2 removes significantly fewer main-sequence stars (right panel of Figure 7). We applied this cut over the excess factor for the three subsamples, as indicated in Table 3.

The final spectral type distribution for the three photometric subsamples is shown in Figure 8 compared to the entire MLSDSS, MLSDSS-GaiaDR2, and astrometric samples. Comparing the MLSDSS and the MLSDSS-GaiaDR2 samples, a significant difference can be observed in the number of late-M and L dwarfs because Gaia DR2 does not contain the faintest stars, so we could not find a match for all MLSDSS objects. The Sub G and Sub Red subsamples are similar to the
dwarfs were removed by the quality cut over the blue sample. However, for the Sub Mix sample, most of late-M dwarfs and all L dwarfs were removed by the quality cut over the blue Gaia band, $g_{\text{BP}}$. We added, for reference, the spectral type distribution of MLSDSS, MLSDSS-GaiaDR2, and the good astrometry sample. Later spectral types are not in the MLSDSS-GaiaDR2 sample, in comparison with MLSDSS, because they are too faint for Gaia and we did not find a match.

The astrometric sample because high-quality G photometry is necessary for the astrometric sample, and only a few stars have low S/N in $g_{\text{RP}}$. The distribution changes significantly for the Sub Mix subsample because the S/N cut for $g_{\text{BP}}$ removed all the L dwarfs and many late-M dwarfs.

To validate all the quality cuts we defined, we plot the color–magnitude diagrams for $M_G$ as a function of the three Gaia colors ($G - g_{\text{RP}}, g_{\text{BP}} - g_{\text{RP}},$ and $g_{\text{RP}} - G$) with and without the previously discussed astrometric and photometric cuts in Figure 9. The photometric cuts remove diagnostic outliers in color and magnitude space in each color and magnitude combination, indicating that they have reliably selected good-quality photometry. Because of the low quality of the $g_{\text{RP}}$ band for the reddest, faintest stars, there is a higher density of red ($G - g_{\text{RP}} > 1.3$) stars in the Sub Red subsample shown on the $(G - g_{\text{RP}})$ diagram. Those stars fall below the main sequence for $(g_{\text{BP}} - g_{\text{RP}})$ and $(g_{\text{RP}} - G)$ in the color–magnitude diagrams without quality cuts applied (Top panels of Figure 9).

3.1. Mean Colors with Gaia DR2

Quantifying the correlation between the new Gaia colors and spectral type is essential to classify new objects and detect outliers. We calculated Gaia DR2 mean colors as a function of spectral type for ($G - g_{\text{RP}}$) using the Sub Red sample and ($g_{\text{BP}} - g_{\text{RP}}$) and $(g_{\text{RP}} - G)$ using the Sub Mix sample (See Section 2.3.2). We removed 2680 stars with extinction correction $E(r - z) > 0.1$ to avoid photometry contaminated by dust in front of the star. The resulting means and standard deviations are shown in Figure 10 and enumerated in Table 4. We fit a second-degree polynomial to the mean color values as a function of spectral type (shown in Figure 10) and give the best-fit parameters in Table 5, where $\sigma$ is the standard deviation of the stars in each bin, which was used to weight the fit. We calculated mean values for M0–L4 for the ($G - g_{\text{RP}}$) color and for M0–M9 for the other two colors because L dwarfs are too faint in the $g_{\text{BP}}$ band and did not pass the quality cuts defined in Section 2.3.

The ($G - g_{\text{RP}}$) color has the tightest relation to spectral type, as shown in the top left panel in Figure 10. The ($g_{\text{BP}} - g_{\text{RP}}$) and ($g_{\text{RP}} - G$) colors have a tight relation for M0 to M7 stars; however, the dispersion increases for later spectral types. Therefore, we conclude that the ($g_{\text{BP}} - g_{\text{RP}}$) color is the best proxy for spectral type for late-M and L dwarfs in the Gaia bands.

The ($G - g_{\text{RP}}$) color locus in Figure 10 has 36 of its most extreme outliers redder (above) of the mean. These outliers have good photometry in $g_{\text{RP}}$ and $G$ bands according to the quality cuts described in Section 2.3.2, but they have low S/N fluxes in the blue band, $g_{\text{BP}}$ (mean_flux_over_error < 10). Inspection of the images of these 36 dwarfs showed that they are binaries or have a close neighbor, which might be causing the excess in the color. These objects were not removed by the excess cut made in Section 2.3 because they have low $S/N$ $g_{\text{BP}}$ photometry. By studying the images, we also confirmed that they were not mismatches. Furthermore, we could not find any peculiarities by plotting these objects in color–color plots for SDSS colors. We concluded that the color excess is likely due to contamination in the $g_{\text{BP}}$ band and we removed them from the analysis. In the MLSDSS-GaiaDR2 sample, these objects are indicated as photometric_sample_subg = 2, photometric_sample_subred = 2, and photometric_sample_submix = 2.

3.2. Mean Absolute Magnitudes with Gaia DR2

We used the MLSDSS-GaiaDR2 sample to calculate mean absolute magnitudes in the three Gaia DR2 bands as a function of spectral subtype of M and L dwarfs using Gaia DR2 parallaxes. We chose the appropriate photometric subsample described in Section 2.3.2 for each band: Sub G for $M_G$, Sub Red for $M_{\text{枹}}$, and Sub Mix for $M_{\text{枹}}$. As in the previous section, we removed stars with high extinction corrections ($E(r - z) > 0.1$) to minimize photometry contaminated by foreground dust. The distributions of absolute magnitudes as a function of spectral subtype are shown in Figure 10 right panels and listed in Table 4.

Note that with the parallax S/N cut applied to the astrometric subsample, we selected a maximum of 10% uncertainty in distance, which corresponds to a maximum of 0.2 mag uncertainty in absolute magnitude (parallax_over_error > 10, see Section 2.3 for details, Lindegren et al. 2018).
For the $G_{BP}$ band, the standard deviation of the distribution of absolute magnitudes per spectral type ($\sigma$) increases toward later spectral types as shown in Table 4. This effect is due to the higher uncertainties in the $G_{BP}$ band for fainter, redder stars (M0 stars have a mean flux S/N in the blue band of phot_bp_mean_flux_over_error = 137 and M8 of phot_bp_mean_flux_over_error = 12). In the $G_{RP}$ and $G$ bands, the standard deviation for late-M dwarfs is one order of

![Figure 9](image_url). Absolute magnitude $M_G$ vs. Gaia DR2 color ($G - G_{RP}$, $G_{BP} - G_{RP}$, and $G_{BP} - G$) for the original MLSDSS-GaiaDR2 sample (without cuts, top panels) and after the astrometric and photometric quality cuts (bottom panels). The color-coding shows the density of sources, where yellow areas are more dense and purple ones are less dense. Two different photometric subsamples were used in the bottom panels: the Sub Red subsample for ($G - G_{RP}$) and the Sub Mix subsample for ($G_{BP} - G_{RP}$) and ($G_{BP} - G$). The Sub Red subsample includes more stars than Sub Mix, resulting in a much higher density of stars along the red ($G - G_{RP} > 1.3$) portion of the main sequence.

### Table 4

| SpT | $G - G_{BP}$ | $G_{BP} - G_{RP}$ | $G_{BP} - G$ | $M_G$ | $M_{G_{RP}}$ | $M_{G_{BP}}$ |
|-----|--------------|-------------------|--------------|-------|-------------|-------------|
| N   | mean | $\sigma$ | N | mean | $\sigma$ | N | mean | $\sigma$ | N | mean | $\sigma$ |
| M0  | 1600 | 0.93 | 0.04 | 1599 | 1.79 | 0.09 | 1599 | 0.87 | 0.06 | 1620 | 8.13 | 0.76 | 1600 | 7.2 | 0.74 |
| M1  | 1473 | 1.01 | 0.04 | 1468 | 2.02 | 0.09 | 1468 | 1.0 | 0.06 | 1506 | 8.78 | 0.83 | 1473 | 7.76 | 0.82 |
| M2  | 2937 | 1.09 | 0.03 | 2934 | 2.25 | 0.09 | 2934 | 1.16 | 0.07 | 2989 | 9.35 | 0.69 | 2937 | 8.26 | 0.67 |
| M3  | 3651 | 1.16 | 0.03 | 3624 | 2.46 | 0.1 | 3624 | 1.31 | 0.08 | 3698 | 9.97 | 0.74 | 3651 | 8.81 | 0.72 |
| M4  | 2855 | 1.23 | 0.03 | 2934 | 2.72 | 0.13 | 2970 | 1.49 | 0.1 | 2889 | 10.77 | 0.77 | 2855 | 9.55 | 0.75 |
| M5  | 1400 | 1.32 | 0.05 | 1311 | 3.02 | 0.19 | 1311 | 1.72 | 0.16 | 1416 | 11.86 | 0.85 | 1400 | 10.54 | 0.81 |
| M6  | 2488 | 1.41 | 0.04 | 969 | 3.39 | 0.19 | 969 | 2.00 | 0.19 | 2510 | 12.92 | 0.73 | 2488 | 11.5 | 0.59 |
| M7  | 2645 | 1.47 | 0.05 | 527 | 3.64 | 0.27 | 527 | 2.22 | 0.26 | 2686 | 13.54 | 0.56 | 2645 | 12.07 | 0.52 |
| M8  | 1093 | 1.57 | 0.05 | 33 | 4.18 | 0.41 | 33 | 2.65 | 0.39 | 1122 | 14.66 | 0.55 | 1093 | 13.02 | 0.51 |
| M9  | 354 | 1.63 | 0.05 | 8 | 4.48 | 0.32 | 8 | 2.91 | 0.32 | 363 | 15.26 | 0.53 | 354 | 13.62 | 0.5 |
| L0  | 119 | 1.67 | 0.04 | 0 | ... | ... | 0 | ... | ... | 121 | 16.11 | 0.44 | 119 | 14.45 | 0.42 |
| L1  | 46 | 1.68 | 0.04 | 0 | ... | ... | 0 | ... | ... | 47 | 16.82 | 0.31 | 46 | 15.14 | 0.31 |
| L2  | 16 | 1.7 | 0.04 | 0 | ... | ... | 0 | ... | ... | 16 | 17.11 | 0.4 | 16 | 15.42 | 0.39 |
| L3  | 6 | 1.69 | 0.02 | 0 | ... | ... | 0 | ... | ... | 6 | 17.89 | 0.59 | 6 | 16.21 | 0.58 |
| L4  | 3 | 1.71 | 0.03 | 0 | ... | ... | 0 | ... | ... | 3 | 18.51 | 0.27 | 3 | 16.8 | 0.25 |
| L5  | 0 | ... | ... | 0 | ... | ... | 0 | ... | ... | 0 | ... | ... | 0 | ... | ... |
| L6  | 1 | 1.77 | 0.0 | 0 | ... | ... | 0 | ... | ... | 2 | 18.92 | 0.17 | 1 | 16.98 | 0.0 |
| L7  | 0 | ... | ... | 0 | ... | ... | 0 | ... | ... | 0 | ... | ... | 0 | ... | ... |

Note. Number of objects included in calculation (N), mean color or magnitude, and standard deviation ($\sigma$) of the mean.
magnitudes for earlier spectral types is associated with low dispersion, where $\sigma$ is the standard deviation. The best-fit third-degree polynomial to the mean values is in a black dashed line and the best-fit polynomial parameters are listed in Table 5.

![Figure 10](image_url)

**Figure 10.** Left panels: Distribution of Gaia DR2 colors as a function of spectral type. We used the photometric subsample Sub Red for ($G - G_{\text{RP}}$) and the Sub Mix subsample for ($G_{\text{RP}} - G_{\text{BP}}$) and ($G_{\text{BP}} - G$) (described in Section 2.3.2). Right panels: Distribution of Gaia DR2 Absolute Magnitudes for the three photometric Gaia bands $G$, $G_{\text{RP}}$, and $G_{\text{BP}}$ as a function of spectral type, using the MLDSS-GaiaDR2 sample. We used the photometric subsamples Sub G, Sub Red, and Sub Mix for $M_{G}$, $M_{G_{\text{RP}}}$, and $M_{G_{\text{BP}}}$, respectively (described in Section 2.3.2). For all the panels, we also show the mean values and 1$\sigma$ and 2$\sigma$ dispersion, where $\sigma$ is the standard deviation. The best-fit third-degree polynomial to the mean values is in a black dashed line and the best-fit polynomial parameters are listed in Table 5.

### Table 5

| Band/Color      | $a$         | $b$         | $c$         | $\sigma$ | Valid Range       |
|-----------------|-------------|-------------|-------------|-----------|--------------------|
| $G - G_{\text{RP}}$ | $-0.0036 \pm 0.0005$ | $0.11 \pm 0.01$ | $0.89 \pm 0.02$ | $0.03$ | M0 $<$ SpT $<$ L4  |
| $G_{\text{BP}} - G_{\text{RP}}$ | $0.012 \pm 0.002$ | $0.19 \pm 0.01$ | $1.81 \pm 0.02$ | $0.09$ | M0 $<$ SpT $<$ M9  |
| $G_{\text{RP}} - G$ | $0.012 \pm 0.001$ | $0.11 \pm 0.01$ | $0.87 \pm 0.01$ | $0.08$ | M0 $<$ SpT $<$ M9  |
| $M_{G}$         | $-0.023 \pm 0.003$ | $1.1 \pm 0.1$ | $7.3 \pm 0.3$ | $0.52$ | M0 $<$ SpT $<$ L4  |
| $M_{G_{\text{RP}}}$ | $-0.008 \pm 0.003$ | $0.8 \pm 0.1$ | $6.8 \pm 0.2$ | $0.47$ | M0 $<$ SpT $<$ L4  |
| $M_{G_{\text{BP}}}$ | $0.03 \pm 0.01$ | $0.7 \pm 0.1$ | $8.9 \pm 0.1$ | $1.24$ | M0 $<$ SpT $<$ M9  |

**Note.** Results from the best fit to the mean absolute magnitudes and colors as a quadratic function of spectral type, $a \times \text{SpT}^2 + b \times \text{SpT} + c$, with M0 = 0, M9 = 9, and L4 = 14, as shown in Figure 10.
metallicity, halo, or thick disk stars, while the scatter toward brighter absolute magnitudes is related to high metallicity, magnetic activity, and/or unresolved binarity. We discuss the relation to age of these particular features in Section 5.

3.3. The SDSS-2MASS-Gaia M and L Dwarf Stellar Locus in Color Space

Previous work (e.g., Covey et al. 2007; Davenport et al. 2014) has shown the power of characterizing the color–color space of the stellar locus to classify stars, detect sources of contamination in a sample, and to calculate extinction corrections. A characterized stellar locus for Gaia colors of M and L dwarfs provides a continuous parameterization of color as a function of effective temperature and facilitates finding color outliers for follow up. Furthermore, incorporating photometry from other surveys provides a relation between colors that will allow us to estimate Gaia DR2 photometry for M or L dwarfs from other catalogs’ colors, or vice versa. We used the MLSDSS-GaiaDR2 sample which contains Gaia \((G, G_{BP}, G_{RP})\), SDSS \((u, g, r, i, z)\), and 2MASS \((J, H, K_s)\) photometry to search for an optimal characterization locus for M and L dwarfs. The characterized stellar locus is shown for \((r - z)\), \((i - z)\), \((i - K_s)\), \((J - K_s)\), \((G_{BP} - G_{RP})\), and \((G_{BP} - G)\) in Figure 11.

We chose \((G - G_{RP})\) as a grounding color because it has the tightest relation to spectral type (see Section 3.1). We used the appropriate photometric subsample described in Section 2.3.2 for each plot: Sub Red for \((r - z)\), \((i - z)\), \((i - K_s)\), \((J - K_s)\), and Sub Mix for \((G_{BP} - G)\) and \((G_{BP} - G_{RP})\). We also selected stars with good SDSS photometry using the GOOD–PHOT_SDSS flag (see Section 2.1 for more details on this cut), including the highest possible number of objects with good photometry in the analysis (median \(S/N \sim 900\) for SDSS photometry, \(\sim 300\) for 2MASS photometry, \(\sim 700\) for \(G\) band, \(\sim 200\) for the \(G_{RP}\) band, and \(\sim 50\) for the \(G_{BP}\) band). We modeled the sequence using a step of \(\delta(G - G_{RP}) = 0.05\) for the full color range covered by M and L dwarfs (0.8 < \((G - G_{BP})\) < 2.0).

Most of the colors have a linear, non-zero-slope relation with \((G - G_{RP})\). The \((r - z)\) and \((i - z)\) linear relations are consistent with previous work (Covey et al. 2007; Davenport et al. 2014; Schmidt et al. 2015). \((J - K_s)\) has a flat relation with \((G - G_{RP})\) for early M and a slightly positive slope for \((G - G_{RP}) > 1.4\), which indicates it is not a good color to distinguish spectral type. This result is consistent with the

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Figure 11. SDSS-2MASS-Gaia M and L dwarfs color–color stellar locus for \((r - z)\), \((i - z)\), \((i - K_s)\), and \((J - K_s)\) for individual stars in density contours (gray) and for mean and standard deviation of the locus (blue points with error bars). We used \((G - G_{RP})\) to calculate the locus, so we chose the photometric subsample Sub Red discussed in Section 2.3.2 and selected stars with good SDSS photometry.
conclusions in Schmidt et al. (2015) for \((J - H)\). The linear relation between \((r - z)\), \((i - z)\), \((i - K_s)\), and \((G - G_{RP})\) breaks for L dwarfs at \((G - G_{RP}) \sim 1.7\). We will discuss this break in Section 4. Finally, \((G_{BP} - G_{RP})\) and \((G_{BP} - G)\) have a tight linear relation with \((G - G_{RP})\). The low dispersion of outliers for these colors is due to the photometric cuts applied to create the subsample Sub Mix.

3.4. Gaia DR2 Color–Magnitude Diagrams

To put the MLSDSS-GaiaDR2 sample in broader stellar context, we compare it to the solar neighborhood \((\leq 100\) pc) sample in the \(M_G\) versus \((G - G_{RP})\) color–magnitude diagram (CMD, Figure 12). Given that we used the red \textit{Gaia} color \((G - G_{RP})\), we used the photometric subsample Sub Red to use the highest number of stars with good photometry in the analysis. We chose this color because it has the tightest relation with spectral type (see Figure 10) and we decided to use \(M_G\) because this band has the smallest photometric error for all stars in the MLSDSS-GaiaDR2 sample (see Figure 6). The solar neighborhood sample shows the full main sequence as well as the beginning of the red giant branch and the white dwarf sequence, while M and L stars from the MLSDSS-GaiaDR2 sample fall at the faint, red end of the main sequence.

The MLSDSS-GaiaDR2 sample color–magnitude diagram is shown again in Figure 13 with SDSS spectral type color-coded. Note that the gap around M5 is due to SDSS selection effects, which were pointed out by West et al. (2011). In this figure, the main sequence widens for stars fainter than \((G - G_{RP}) \sim 1.05\). This effect could be related to the transition into fully convective low-mass stars.

For earlier-type stars \((G - G_{RP} < 1.3)\), there is a significant number of objects below the main sequence. These objects are likely to be low metallicity, old stars. This faint outlier population is not present for later types \((G - G_{RP} > 1.3)\). This is not likely to be a result of the quality cuts we made in Section 2.3 because the scatter is not present when there are no cuts applied (see Figure 9). The lack of scatter in the region where subdwarfs typically lie for later types could be a selection effect from SDSS or a physical difference in the colors of later-type subdwarfs (which could be less blue than their earlier spectral type counterparts; West et al. 2004; Lépine & Scholz 2008). To corroborate that the stars scattered below the main sequence are primarily subdwarfs, we cross-matched MLSDSS-GaiaDR2 with the catalog of subdwarfs from Savcheva et al. (2014). From this cross-match we found 376

Figure 12. Color–magnitude diagram for the MLSDSS-GaiaDR2 sample color-coded with its density map with the quality cuts described in Section 2.3 applied, compared to 100 pc sample from \textit{Gaia} DR2 in gray, also color-coded with its density map. To clean the MLSDSS-GaiaDR2 sample, we used the quality cuts in the photometric subsample Sub Red.

Figure 13. Color–magnitude diagram for the MLSDSS-GaiaDR2 sample, color-coded by spectroscopic spectral type. To clean the MLSDSS-GaiaDR2 sample, we used the quality cuts in the photometric subsample Sub Red, as in Figure 12.

Figure 14. Contours in gray of the color–magnitude diagram of MLSDSS-GaiaDR2 with the 376 matches with the subdwarfs from Savcheva et al. (2014). We distinguish between subdwarfs (sdMs; light green), extreme subdwarfs (esdMs; green), and ultrasubdwarf (usdMs; dark green) as assigned by Savcheva et al. (2014) using the metallicity proxy \(\zeta\). We note that most subdwarfs fall below the main sequence as expected.
subdwarfs in the MLSDSS-GaiaDR2 sample that had good photometry and astrometry according to our quality cuts (Section 2.3). In Figure 14 we show a color–magnitude diagram of these 376 subdwarfs compared to the MLSDSS-GaiaDR2 sample. We also included the distinction between subdwarfs (sdMs), extreme subdwarfs (esdMs), and ultrasubdwarfs (usdMs) according the metallicity proxy ($\zeta$) (Lepine et al. 2007; Dhital et al. 2012). As expected, the esdMs fall the furthest below the main sequence, with the usdMs and sdMs falling progressively closer to main-sequence stars, consistent with Savcheva et al. (2014). However, some of the Savcheva et al. (2014) subdwarfs fall on the main sequence of our color–magnitude diagram. Many of these stars have relatively low S/N spectra and may have been misclassified as subdwarfs in that work.

Bochanski et al. (2013) found that the separation between subdwarf types was $\sim$1 mag in $M_r$ at a given $r-z$ color or spectral type, which is approximately the same separation we observe in Figure 14 for $M_G$ at a given $G - G_{RP}$. The position of the subdwarfs in the color–magnitude diagram is also consistent with other work on metal-poor M dwarfs (see for e.g., Lepine et al. 2007; Jao et al. 2008, 2017).

There are also sources scattered above the main sequence, likely caused by M dwarf binaries, high metallicity, magnetic activity (see Section 5.1), and dust contamination in Gaia bands (see Section 2.2). Note that some of the most distant stars from the main sequence could be binaries with an M dwarf primary and a giant companion (Gaia Collaboration et al. 2018a). The scatter above and below the main sequence is discussed in more detail in Section 5.

4. M and L Dwarf Absolute Magnitudes in SDSS and 2MASS Bands

Gaia DR2 distances are an order of magnitude more precise than the photometric distances in MLSDSS (uncertainties of $\sim$5% versus $\sim$20%), allowing us to calculate absolute magnitudes with a median error of 0.15 mag for SDSS photometry and 0.12 mag for 2MASS photometry. We recalculated the relationship between absolute magnitudes

![Figure 15. Distribution of absolute magnitudes as a function of spectral type for SDSS and 2MASS photometry. We show the mean values and the 1σ and 2σ dispersion, where σ is the standard deviation per bin of spectral type. In a black dashed line, we show the second-order polynomial fit to these data, with parameters listed in Table 6. In light gray we show the outliers for each relation. We include results from Hawley et al. (2002) in blue for comparison.](image-url)
and spectral type for SDSS and 2MASS photometry with these new values and the relationship between absolute magnitudes and the \((r - z)\) color. These relations are useful to estimate spectrophotometric and photometric distances for stars that are not in \textit{Gaia} DR2, as shown by previous work, which was based on fewer than 100 stars with parallaxes (e.g., Hawley et al. 2002; Bochanski et al. 2010). We caution, however, that because the MLSDSS-GaiaDR2 sample has not been vetted for binaries and low metallicity stars, it may be subject to biases not present in the previous, smaller samples.

To generate the most accurate relationship between absolute magnitudes and spectral type and color, we applied the astrometric cuts discussed in Section 2.3.1 and the photometric cut for SDSS photometry discussed in Section 2.1, thereby selecting objects with the best astrometry and photometry available. The distribution of absolute magnitudes as a function of spectral type is shown in Figure 15 and as a function of color in Figure 16.

For each spectral type, we calculated the mean value and the standard deviation \((\sigma)\) in absolute magnitude. We also performed a fit to the mean values as a function of spectral type with \(\sigma\) as weights. The fit only extends to spectral type L4 because of the small number of later-type objects; most objects later than L4 are too faint to be in \textit{Gaia} DR2 and so cannot be included (See Section 2.2). The best-fit parameters for SDSS \(riz\) and 2MASS \(JHK_s\) absolute magnitudes are listed in Table 6.

### Table 6

| Band   | \(a\)       | \(b\)       | \(c\)       | \(\sigma\) |
|--------|-------------|-------------|-------------|------------|
| \(M_r\) | \(-0.03 \pm 0.01\) | \(1.3 \pm 0.1\) | \(7.2 \pm 0.4\) | \(0.62\) |
| \(M_i\) | \(-0.009 \pm 0.004\) | \(0.9 \pm 0.1\) | \(6.8 \pm 0.2\) | \(0.55\) |
| \(M_z\) | \(-0.005 \pm 0.003\) | \(0.74 \pm 0.05\) | \(6.7 \pm 0.2\) | \(0.5\) |
| \(M_J\) | \(-0.007 \pm 0.002\) | \(0.65 \pm 0.04\) | \(5.7 \pm 0.1\) | \(0.47\) |
| \(M_H\) | \(-0.012 \pm 0.002\) | \(0.69 \pm 0.03\) | \(5.0 \pm 0.1\) | \(0.48\) |
| \(M_{Ks}\) | \(-0.012 \pm 0.002\) | \(0.66 \pm 0.03\) | \(4.8 \pm 0.1\) | \(0.47\) |

\textbf{Note.} Best-fit parameters to a quadratic fit to SDSS and 2MASS absolute magnitudes as a function of spectral type, \(M = a \times \text{SpT}^2 + b \times \text{SpT} + c\), as shown in Figure 15. The fit was based on stars with spectral types M0–L4.
For comparison, we included the mean values as a function of spectral type calculated by Hawley et al. (2002) from a sample of 718 M and L dwarfs with photometric distances. We note that our fit for $M_r$, $M_i$, and $M_z$ lies above the values calculated by that work. This is likely in part because of the uncertainties in the photometric distance, but also may be because of the binary population in our sample when performing the fit: binary systems with two equal mass components fall 0.7 mag above the main sequence, which could result in brighter mean absolute magnitude.

While most of the MLSDSS-GaiaDR2 sample follows the mean trend for absolute magnitude as a function of spectral type, there are outliers in each spectral type bin that are more than $2\sigma$ from the mean in absolute magnitude. These outliers have a distribution similar to that in the $Gaia$ photometric color–magnitude diagram (Figure 13). Those scattered to fainter absolute magnitudes can be associated with low metallicity stars and are only present for earlier spectral types. The scatter toward brighter absolute magnitudes is mostly present for early and mid-M dwarfs and can be associated with binarity, high metallicity, and/or magnetic activity. We will discuss more this scatter in Section 5.

We also examined the relationships between SDSS $riz$ and 2MASS $JHK_s$ absolute magnitudes as a function of the $(r - z)$ color. We selected $(r - z)$ as the base color because it is a good indicator of spectral type/effective temperature for M dwarfs.

For $M_r$, $M_i$, $M_z$, we divided the $(r - z)$ axis in intervals of 0.5 mag and calculated the mean value and standard deviation for each interval. We fit the mean values with a third-degree polynomial using the standard deviations as weights. We performed a fit for $0.5 < r - z < 4.5$ mag (corresponding to M0–M9 dwarfs) because for L dwarfs, the main sequence turns over, as shown in Figure 16. This is the same break shown in the stellar color locus analysis in Figure 11 at color $(G - G_{BP}) \sim 1.7$. It means the relation between absolute magnitude and color cannot be used beyond this point because the two quantities are no longer related in the same way. The best-fit parameters are in Table 7.

We find that $M_r$ has the tightest relation with $(r - z)$ color. The spread above and below the main sequence increases for the i- and z-bands. Furthermore, all three 2MASS bands (right panels) have higher spread above and below the main sequence than SDSS bands, and it also increases for the $K_s$ bands in comparison with $J$ and $H$. We compared our data and fit in $M_r$ versus $(r - z)$ to the fit from Bochanski et al. (2010) as a check on our accuracy. The two fits are in good agreement, and both fall over the highest density of data points.

### 5. Age-related Parameters

One of the primary goals for analysis of the MLSDSS-GaiaDR2 sample is to calibrate observable age indicators for M and L dwarfs. In this section, we examine the following activity-related and kinematic age indicators: (1) fractional Hα luminosity ($L_{H\alpha}/L_{bol}$), (2) vertical velocity dispersion ($\sigma_v$), (3) vertical action dispersion ($\sigma_z$), and (4) tangential velocity ($v_t$). The relationship between Hα, kinematics, and age has been explored in previous works (e.g., West et al. 2008b; Pineda et al. 2013). However, our kinematics significantly improve the 20% uncertainties on MLSDSS data as $Gaia$ DR2 contains proper motions with uncertainties of 1% and distances with uncertainties of 5%.

#### 5.1. Fractional Hα Luminosity on the Gaia Color–magnitude Diagram

Fractional Hα luminosity ($L_{H\alpha}/L_{bol}$) is a parameterization of the strength of the chromospheric Hα emission line that removes the dependence on the continuum that is a factor with EW measurements. This fractional Hα luminosity is an age indicator because it is a measure of stellar magnetic activity, which is presumed to be age dependent: young stars have higher magnetic activity, while old stars are less active or inactive (e.g., Skumanich 1972; Baliunas et al. 1995; Donahue et al. 1996; Mamajek & Hillenbrand 2008; West et al. 2008a).

We show the relationship between fractional Hα luminosity and the position of the star on the $Gaia$ color–magnitude
from our sample, we believe that metallicity and, for the active stars, radius (members with known ages: Taurus plot for the full sample as in the top panel with three known moving groups known young moving groups from Gagné & Faherty magnitude position of the active stars with the position of three fl effect of metallicity and radius in direction for increasing metallicity in the color effective temperature at approximately 7 Gyr et al. 2000; West et al. 2004, 2008a; Schmidt et al. 2015 long main sequence. The high fraction of active stars is due to the high SDSS extinction, meaning that these effects should mostly cause horizontal shifts on the color–magnitude diagram, not vertical ones.

Youth, binarity, metallicity, and activity can all play a role in scattering M0–M5 stars, shown in the top panel of Figure 18 to redder colors and/or brighter magnitudes than the bulk of the main sequence. Metallicity and binarity effects seem combined with activity to lift stars further off the main sequence; however, it is unlikely that our active stars are particularly young. Magnetism likely plays a strong role in the position of active stars on the color–magnitude diagram. This effect might also exist for the later spectral types (>M5) but it is not evident in our current analysis.

Figure 18. Top panel: Zoom in of Figure 17. We included a reference to the effect of metallicity and radius inflation due to magnetic activity (lower effective temperature at approximately fixed luminosity) on the position of stars in the color–magnitude diagram with two arrows. These show an approximate direction for increasing metallicity (Z) and constant bolometric luminosity (βB) calculated from Mann et al. (2015). Lower panel: We show the same contour plot for the full sample as in the top panel with three known moving groups members with known ages: Taurus (TAU, 1–2 Myr), β Pictoris (βPMG, 24 ± 3 Myr), and Carina-Near (CARN, ~200 Myr). Active stars on the top panel look as young as 24 Myr, but as this is not consistent with what we know from our sample, we believe that metallicity and, for the active stars, radius inflation are the causes of the scattered data.

As shown in Figure 17, the majority of the low-mass red stars (G − G_RP > 1.3; <M5) are both active and fall along the main sequence. The high fraction of active stars is due to the long (~7 Gyr) active lifetimes of late-M and L dwarfs (Gizis et al. 2000; West et al. 2004, 2008a; Schmidt et al. 2015). We find a clear correlation between activity and the position in the color–magnitude diagram for the bluer ((G − G_RP) < 1.3; <M5) stars and in Figure 18, we zoom into this region. Active stars are found, on average, at redder colors and/or brighter magnitudes than inactive stars. The four most probable causes are youth, metallicity, binarity, and/or magnetic activity. The effects of each are described below.

To investigate the effect of youth, we compared the color–magnitude position of the active stars with the position of three known young moving groups from Gagné & Faherty (2018): Taurus (TAU, 1–2 Myr), β Pictoris (βPMG, 24 ± 3 Myr), and Carina-Near (CARN, ~200 Myr; Figure 18). The oldest of the moving groups, CARN, is the closest to the main sequence, while the younger groups fall above it, mostly because of the stars still contracting and having larger radii than stars of the same mass that have reached the main sequence. While these young stars are active, they are, on average, not as active as the most strongly active stars in the MLSDSS-GaiaDR2 sample. Therefore, we speculate that their position above the main sequence is primarily due to their pre-main-sequence radius rather than their activity level. The comparison between these young stars and the active MLSDSS-GaiaDR2 stars provides an estimate of how much radius inflation due to youth is responsible for their position on the color–magnitude diagram.

In Figure 18, we show that active MLSDSS-GaiaDR2 stars that lie just above the main sequence have approximately the same position as the 24 Myr moving group βPMG. However, these active stars are unlikely to be young: they are within 200 pc from the Sun but there are a limited number of associations at or around 24 Myr at these nearby distances (e.g., 32 Orionis, see Faherty et al. 2018), and none of these stars appear to be members of known young groups. Furthermore, most of the early-M dwarfs in MLSDSS-GaiaDR2 are highly separated from the plane of the Galaxy which indicates they are old (e.g., West et al. 2004). Therefore, the position of the active stars at redder colors and/or brighter magnitudes than inactive stars is not due entirely to youth.

Binarity could also affect the position of active stars in the color–magnitude diagram. Tight binaries are more luminous and could be more active because of tidal interactions (Shkolnik et al. 2011).

Another factor that influences the position of stars on the color–magnitude diagram is its metallicity. Mann et al. (2015) showed that high metallicity M dwarfs tend to have larger radii than low metallicity M dwarfs for a given effective temperature. This effect could be another factor in the position of active stars on the color–magnitude diagram.

Moreover, Bochanski et al. (2011) showed that active stars fall even redder and/or brighter above the main sequence than inactive stars with the same metallicity. Active stars have been shown to have inflated radii, possibly caused by strong surface magnetic fields (e.g., Lopez-Morales & Ribas 2005; Morales et al. 2009; Torres 2013). Observations of young low-mass stars show radii that are, at a fixed mass, 10%–15% larger than predicted by evolutionary models (e.g., Somers & Stassun 2017; Cruz et al. 2018; Kesseli et al. 2018). Stassun et al. (2012) showed that for low-mass stars, the activity strength of active stars (as indicated by L_Hα/L_bol and L_Xray/L_bol) is correlated with inflated radii and cooler effective temperatures compared to inactive stars. They also found that radius inflation and cooler temperatures cancel the effect of magnetic activity on bolometric luminosity, meaning that these effects should not be important.
5.2. Vertical Velocity and Vertical Action Dispersion

Full three-dimensional space motion has been shown to trace stellar ages in the Galaxy. As stars age, increased interactions with giant molecular clouds and passing stars result in kinematic heating. Therefore, one can use the overall velocity distribution of a population of stars to infer the age of that population via an age–velocity dispersion relation (e.g., Wielen 1977; Hänninen & Flynn 2002). Previous works have used full kinematics, or tangential velocity, as a proxy for full space motion, to estimate the kinematic age of the low-mass star population compared to higher mass stars (e.g., Schmidt et al. 2007; Zapatero Osorio et al. 2007; Faherty et al. 2009; Reiners & Basri 2009). Vertical action is related to the vertical component of a star’s angular momentum integrated over the gravitational potential of the Milky Way. Previous work has shown that, in particular, vertical velocity and vertical action dispersion (\(\sigma_W\) and \(\sigma_J\)) are correlated with age (e.g., Nordstrom et al. 2004; West et al. 2006, 2008a; Aumer et al. 2016; Yu & Liu 2018). As we do not have ages for the stars in the MLSDSS-GaiaDR2 sample yet, we studied the correlation between \(\sigma_W\) and \(\sigma_J\) and fractional \(H\alpha\) luminosity, another age indicator (see Section 5.1 for the \(H\alpha\) analysis).

We calculated vertical actions and vertical velocities using positions, proper motions, and parallaxes from Gaia DR2 and radial velocities from MLSDSS. Note that the stars in the MLSDSS-GaiaDR2 sample are too faint to have radial velocities in Gaia DR2. For this analysis we used the good astrometric sample described in Section 2.3.1 and we added cuts for radial velocity \(S/N: rv/rv_{\text{err}} > 2\) and absolute value: \(|rv| < 500\) km s\(^{-1}\). The number of stars after the extra cuts for radial velocity is 15,988 (67% of the good astrometric sample of 23,842 stars). We also removed stars categorized as white dwarf-M dwarf binaries because the white dwarf can affect the magnetic field of the companion (see Section 2.1, Morgan et al. 2012). To compute vertical velocities and vertical actions, we used Galpy\(^9\) (Binney 2012; Bovy & Rix 2013; Bovy 2015) and W. Trick’s code\(^10\) with the Milky Way potential from Bovy (2015). Uncertainties on these values were computed via Monte Carlo.

To compute the dispersion, we divided the values of logarithmic fractional \(H\alpha\) luminosity \((\log_{10}(L_{H\alpha}/L_{bol}))\) into six regularly spaced bins and calculated the dispersion per bin \((\sigma_{\text{bin}})\). The value of fractional \(H\alpha\) luminosity assigned to each \(\sigma_{\text{bin}}\) corresponds to the middle of the bin. To calculate the dispersion per bin, we used the median absolute deviation to alleviate the influence of outliers. Uncertainties on the median absolute deviation were estimated, again by performing Monte Carlo resampling of data points within their uncertainties.

Results for the dispersion of vertical velocity as a function of \(H\alpha\) luminosity are presented in Figure 19. We divided the data into three spectral type bins: \(\text{SpT} \leq M4\), \(M5 \leq \text{SpT} < M8\), and \(M8 \leq \text{SpT}\), as well as two categories of active and inactive stars (see Section 2.1 for more detail on the classification of active and inactive). For the active stars, we find that \(\sigma_W\) is lower for high-\(H\alpha\)-activity stars than for less-active stars, and inactive stars have a higher vertical velocity dispersion than do active stars on average. Magnetically active stars are younger than less-active or inactive stars (e.g., Skumanich 1972; West et al. 2008a); therefore, Figure 19 is showing that vertical velocity is also correlated with age: young stars have a smaller vertical velocity dispersion because they have had less time to experience orbital perturbations in the \(Z\) direction (out of the galactic plane).

The activity-velocity dispersion relation does not show an obvious dependence on spectral type, which is a proxy for mass for mid and late dwarfs \((\text{SpT} > M5)\). Active early-M dwarfs have higher vertical velocity dispersions compared to later-type dwarfs. This is likely due to the detection threshold for the proper motions of the most distant M dwarfs; those with lower tangential velocities have lower quality proper motions, so only stars with high velocities have reliable proper motions, therefore biasing the dispersion to larger values (Bochanski et al. 2011). Moreover, the sample of early-M dwarfs is biased toward old stars compared to the sample of mid- to late-M dwarfs because of selection effects. The SDSS photometric dispersion relation is presented in Figure 20. We used the same age cuts as for Figure 19; the error bars are the 16th and 64th percentiles.

\[^9\] http://github.com/jobovy/galpy
\[^10\] https://github.com/wilmatrix/GaiaSprint/blob/master/Action_Galpy_ Tutorial.ipynb
detectors saturated for sources brighter than 14 mag in r cannot obtain reliable photometry for M0 – M4 dwarfs found closer than 100–200 pc to the Sun. On the faint end, SDSS spectra only have sufficient quality to be included in the sample of objects brighter than $\sim$23 mag in r, including early-M dwarfs as distant as $\sim$1–2 kpc, but late-M dwarfs only are detected at a distance of $\sim$100–200 pc. As a consequence, early-M dwarfs found in the MLSDSS-GaiaDR2 sample are typically higher above the plane of the Galaxy and so they are likely older than later-type M dwarfs.

We calculated vertical action using a procedure similar to that used to calculate vertical velocity, and Figure 20 shows vertical action dispersion as a function of fractional H$\alpha$ luminosity. In this case, not all of the vertical action distributions are Gaussian, so the distributions of dispersion per bin are also not a Gaussian. Therefore, we represent the uncertainties with the 16th and 64th percentiles. Similarly to the vertical velocity analysis, inactive stars have significantly larger vertical action dispersion than active stars, and for active stars, the dispersion decreases with increasing H$\alpha$ activity. This indicates that vertical action dispersion, similar to the vertical velocity dispersion, is another age indicator: young stars have low vertical action dispersion, while old stars have higher dispersion because they were kinematically heated. Early-M dwarfs in Figure 20 seem to have higher vertical action dispersion; however, this is likely due to the same biases from distant M dwarfs explained above.

Figures 19 and 20 are the first steps to obtaining a functional description of how kinematics indicate the age of low-mass stars (e.g., work such as Wielen 1977 for higher mass stars).

5.3. Tangential Velocity

With Gaia DR2 we were able to calculate precise tangential velocities for 22,373 M and L dwarfs in the MLSDSS-GaiaDR2 sample. To explore the disk and halo populations of stars in our catalog, we studied the correlation between tangential velocity ($v_{\text{tan}}$) and color–magnitude diagram position for the MLSDSS-GaiaDR2 sample (Figure 21) as done by previous work (Gizis & Reid 1999; Lepine et al. 2007; Jao et al. 2017).

There is a significant number of stars below the main sequence for $(G - G_{\text{RP}}) < 1.3$ that have a high tangential velocity, with $v_{\text{tan}} \sim 200$ km s$^{-1}$, in comparison to the rest of the stars in the sample, with $v_{\text{tan}} \sim 50$ km s$^{-1}$. Such objects that are blue and fast are likely members of the older thick disk or halo. At least half of these stars were classified as subdwarfs by Savcheva et al. 2014 (See Section 3.4). These high tangential velocity objects also have low fractional H$\alpha$ luminosities (see Figure 17). The lack of magnetic activity paired with high tangential velocities, low metallicities, and blue optical colors affirms they are likely an older population of low-mass stars.

6. Summary

We compiled the MLSDSS-GaiaDR2 sample of 74,216 M and L dwarfs. To create the sample, we combined two SDSS catalogs: the SDSS DR7 M dwarfs spectroscopic catalog (West et al. 2011) and the BUD catalog (Schmidt et al. 2015, S. J. Schmidt et al. 2019, in preparation), into the MLSDSS sample. H$\alpha$ EWs, spectral types, and radial velocities were calculated by the authors of these catalogs. We cross-matched the MLSDSS sample with Gaia DR2 to obtain proper motions and parallaxes for the stars. We found 73,003 matches and we used a very conservative criterion to identify 67,573 good matches. We adjusted some of the quality cuts suggested by the Gaia Papers (e.g., Arenou et al. 2017; Evans et al. 2018; Lindegren et al. 2018; Gaia Collaboration et al. 2018a) to make them suitable for the later M and L dwarfs. The final MLSDSS-GaiaDR2 sample contains H$\alpha$ EWs, spectral types, SDSS, 2MASS, and Gaia photometry and proper motions and parallaxes from Gaia DR2. The good astrometric sample contains 23,842 stars, and the good photometry sample for the $G$, $G_{\text{RP}}$, and $G_{\text{BP}}$ bands have $22,706$, $22,373$, and $16,527$ stars, respectively.

With the MLSDSS-GaiaDR2 sample we calculated mean absolute magnitudes and colors as a function of spectral type using the three photometric bands in Gaia DR2: $G$, $G_{\text{RP}}$, and $G_{\text{BP}}$. Furthermore, we characterized the color–color space of the stellar locus for Gaia, SDSS, and 2MASS colors. We used the distances calculated with Gaia DR2 parallaxes, which are one order of magnitude better than the photometric distances from MLSDSS, to plot the color–magnitude diagram for the MLSDSS-GaiaDR2 sample. We found that the H$\alpha$ main sequence widens as it goes toward cooler stars. This effect starts around spectral type M3 and could be related to the transition to fully convective interior. We also used the MLSDSS-GaiaDR2 SDSS and 2MASS photometry to calculate absolute magnitudes as a function of spectral type and color for the $riz$-photometry and $J$, $H$, and $K_s$ bands. We compared our results with those of Hawley et al. (2002) and Bochanski et al. (2011) and found good agreement.

We noticed that active stars are found, on average, at redder colors and/or brighter magnitudes than inactive stars in the color–magnitude diagram. Comparing to the position in the color–magnitude diagram of three young moving groups with different ages, we found that youth alone cannot explain the position of active stars. The stars in the MLSDSS-GaiaDR2 sample are mostly high above the galactic plane and, therefore, unlikely to be young. We hypothesize that the position of
active stars might be due to binarity, metallicity, and/or that magnetism likely plays a strong role by inflating the radii of the stars and reducing their effective temperature, which makes them look redder.

Furthermore, we found that early types of inactive stars that are faint in absolute magnitude (below the main sequence) have high tangential velocities (~150 km s\(^{-1}\)), which indicates they belong to the halo or thick disk and that they are an old population of M dwarfs. Furthermore, 376 of these were identified as subdwarfs by Savcheva et al. (2014).

Finally, we studied the relation between vertical velocity and vertical action dispersion with fractional H\(\alpha\) luminosity. We found that stars with higher H\(\alpha\) activity have lower dispersion both in vertical velocity and vertical action and stars with lower H\(\alpha\) activity or inactive stars have higher dispersion. As H\(\alpha\) is an age indicator, this means that young (active) stars live close to the plane of the galaxy, so their vertical action and vertical velocity dispersion is small, and old (less-active or inactive) stars were kinematically heated, so their dispersion is higher. In future work, we will fit these relations using bayesian inference and we will constrain the ages of M and L dwarfs using the age indicators in the MLSDSS-GaiaDR2 sample.

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