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USING THE GALACTIC DYNAMICS OF M7 DWARFS TO INFER THE EVOLUTION OF THEIR MAGNETIC ACTIVITY

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ABSTRACT

We present a spectroscopic study and dynamical analysis of ∼2600 M7 dwarfs. We confirm our previous finding that the fraction of magnetically active stars decreases with vertical distance from the Galactic plane. We also show that the mean luminosity of the Hα emission has a small but statistically significant decrease with distance. Using space motions for ∼1300 stars and a simple one-dimensional dynamical simulation, we demonstrate that the drop in the activity fraction of M7 dwarfs can be explained by thin disk dynamical heating and a rapid decrease of magnetic activity at a mean stellar age of ∼6–7 Gyr.

Key words: Galaxy: kinematics and dynamics — Galaxy: structure — solar neighborhood — stars: activity — stars: late-type — stars: low-mass, brown dwarfs

1. INTRODUCTION

The most ubiquitous stars in the Galaxy are low-mass dwarfs. Because they are plentiful, they provide an excellent probe of the structure and dynamics of the local thin disk stellar population. In addition, many low-mass dwarfs are magnetically active (as identified by Hα emission), especially the mid-to-late M dwarfs. Various studies have suggested that there is a relation between the magnetic activity of an M dwarf and its age. These studies have used the Galactic motions of M dwarfs (Wilson & Woolley 1970; Wielen 1977; Hawley et al. 1996), M dwarf activity in stellar clusters (Hawley et al. 1999, 2000; Gizis et al. 2002), and active M dwarfs in binary systems (Silvestri et al. 2005, 2006). By using the activity of M dwarfs and the largest spectroscopic sample of M dwarfs ever assembled, we can augment dynamical and positional data with the additional parameter of time.

Previous studies have thoroughly investigated the vertical dynamics and structure of the Galaxy. Wielen (1977) found that the velocity dispersion of stars increases with time to the 0.5 power ($t^{0.5}$). Spitzer & Schwarzschild (1951, 1953) suggested that massive gas clouds would cause an increase in the velocity dispersion of stars through cloud-star interactions. Subsequent observations of molecular clouds confirm that enough interstellar gas exists to dynamically heat disk stars. However, current evidence indicates that molecular clouds alone are not responsible for the total amount of heating. Black holes and spiral density waves have been suggested as other possible contributors to the heating of the Galactic disk (Jenkins 1992; Hänninen & Flynn 2002).

Recently, many groups have investigated the structure and age of the Galactic disk by examining the observed and simulated kinematics of nearby stars (Kuijken & Gilmore 1989; Dehnen & Binney 1998; Rocha-Pinto & Maciel 1998; Binney et al. 2000; Fuchs et al. 2001; Hänninen & Flynn 2002; Holmberg et al. 2003; Siebert et al. 2003). The values reported for the exponent (α) of the time dependence (t^{α}) of the velocity dispersion have not converged and range from 0.26 to 0.59 (in most cases the uncertainties in α are smaller than this spread). Despite the discrepancies, these studies have aided in constraining the age of the solar neighborhood, the surface mass density of the Galactic plane, and the time evolution of dynamical heating. Most of this work has not used low-mass stars due to the small numbers of M dwarfs included in magnitude-limited samples. Aside from the initial work by Wielen (1977) and the more recent Palomar/Michigan State University and 100 pc surveys (Reid et al. 2002; Bochanski et al. 2005), few Galactic studies have examined the low-mass stellar constituents.

The advent of large-survey science has vastly increased the number of low-mass dwarfs available for analysis. Using several hundred M7 dwarfs from the Sloan Digital Sky Survey (SDSS), West et al. (2004; hereafter W04) suggested that the fraction of activity in M7 stars decreases as a function of height above (or below) the Galactic plane. They suggested that this phenomenon would naturally result from an age-activity relation; the older stars are, on average, farther away and are no longer active, thus decreasing the active fraction. However, despite using hundreds of stars in their analysis, the W04 results had large uncertainties.

In this paper we focus on the activity and dynamics of a much larger sample of M7 dwarfs. We describe our selection criteria and data in § 2. In § 3 we confirm the findings of W04, namely, that the fraction of activity decreases as a function of vertical distance from the Galactic plane. We also investigate how the magnitude of activity (as quantified using $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$) changes with distance. We use proper motions from the USNO-B catalog (Monet et al. 2003) and a new set of low-mass star templates for measuring radial velocities (Bochanski et al. 2007) to derive space motions. In § 4 we use a simple dynamical simulation to explain the decline in activity fraction as due to dynamical heating effects, and we derive a timescale for the existence of magnetic activity in M7 dwarfs. Our results are discussed and plans for future projects proposed in § 5.

2. DATA

The SDSS (Gunn et al. 1998, 2006; Fukugita et al. 1996; York et al. 2000; Hogg et al. 2001; Ivezić et al. 2004; Pier et al. 2003; Smith et al. 2002; Stoughton et al. 2002) provides ideal samples

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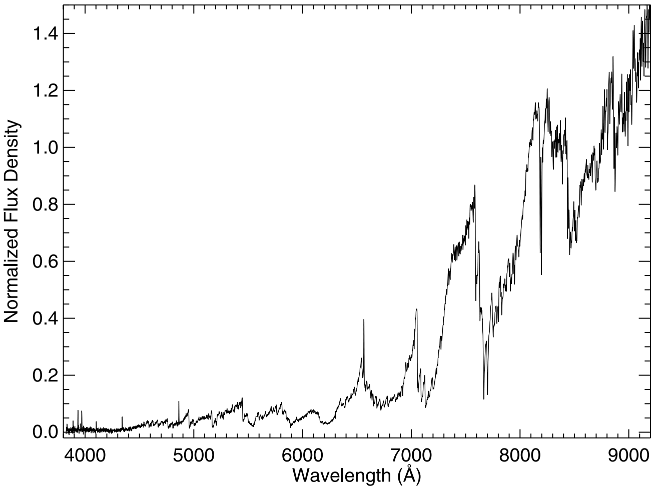

FIG. 1.— Co-added template spectra for all SDSS stars in our M7 sample. Spectra are shifted to zero velocity and placed on a finer resolution grid to produce more accurate radial velocities (see Bochanski et al. 2007 for more details).

to examine the spectral and photometric properties of low-mass dwarfs. Many studies have already taken advantage of the unprecedented large sample sizes and uniform data quality that SDSS offers for cool-star research (Hawley et al. 2002; W04; Silvestri et al. 2006). In this study we continue the analysis originally discussed in W04, concentrating on M7 dwarfs. This spectral type was selected because of the large number of M7 dwarfs in the sample and their high activity fraction.

Our sample is drawn from the SDSS Data Release 4 (DR4; Adelman-McCarthy et al. 2006). A total of 4420 stars were selected from the SDSS spectroscopic database based on the colors typical of M7 dwarfs ($1.92 < r - i < 2.65$ and $1.06 < i - z < 1.45$; West et al. 2005). Because there is some overlap with M6 and M8 stars, this sample contains all three spectral types but is dominated by M7s. Nearby M7 dwarfs are too bright for SDSS spectroscopy. Therefore, 171 additional M7 dwarfs were added from the nearby Two Micron All Sky Survey (2MASS)–selected sample of Cruz et al. (2003) to add sensitivity to our sample at low Galactic heights. We examined each spectrum by eye using the Hammer stellar spectral-typing facility (K. R. Covey et al. 2006, in preparation). We removed 232 spectra because they were identified as galaxies or binary systems or had poor data quality.

We performed the spectral activity analysis described in W04 on the entire M7 sample. There were 2601 stars that had the requisite data quality (using the same criteria as W04) for a statistically robust analysis. The resulting sample contains 3 times more M7 dwarfs than that of W04. We found that 1828 of the stars were active and 773 were not active, giving a 70% ± 2% active fraction, similar to the 64% ± 3% M7 activity fraction found in W04. Some of the discrepancy is due to the addition of the Cruz et al. (2003) sample that consists almost entirely of active stars (because they are nearby). Using the method of Walkowicz et al. (2004), we also computed the ratio of luminosity in the Hα line to the bolometric luminosity ($L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$) for all stars in the sample. We averaged the χ values for the M6.5, M7, M7.5, and M8 spectral types for determining the $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$ ratios. Distances to all stars were calculated using the photometric parallax methods of Walkowicz et al. (2004) and West et al. (2005). Using the positions and distances of each star, Galactic height was computed, assuming that the Sun is 27 pc above the plane (Chen et al. 2001).

We used the SDSS/USNO-B matched catalog to obtain proper motions. The USNO-B proper motions were obtained for 1180 of the 2601 good-quality SDSS stars. To maintain a uniform sample of space motions, we did not include the Cruz et al. (2003) data in our dynamical analysis. Radial velocities were measured for all SDSS stars using the method described in Bochanski et al. (2007), by which co-added, zero-velocity SDSS spectra were used to create high signal-to-noise ratio (S/N) radial velocity templates. Figure 1 shows the resulting template from the co-addition of all stars in our M7 sample. Our derived radial velocities are accurate to within $\sim$5 km s^{-1}. Using these proper motions and radial velocities, space motions were computed for all SDSS stars.

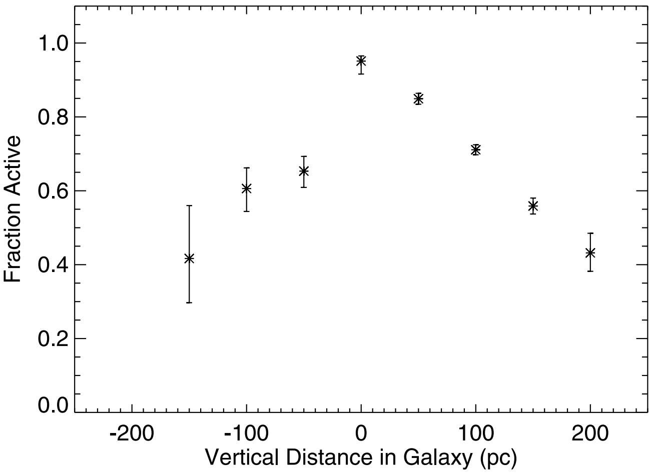

FIG. 2.— Fraction of active stars as a function of vertical distance above and below the Galactic plane. The stars have been binned every 50 pc. Active stars are concentrated toward the plane, and the fraction decreases on either side. Using an age-activity relation and assuming dynamical heating, we infer that the stars closer to the Galactic plane are younger and that the decline in activity fraction is likely due to the termination of magnetic activity in older stars.

3. OBSERVATIONAL RESULTS

Figure 2 shows the fraction of active M7 dwarfs in 50 pc bins as a function of height from the Galactic plane. This figure confirms the result of W04: the fraction of active M7s decreases as a function of distance from the Galactic plane. Because these data are binomial in nature, the uncertainties are asymmetric and were calculated using the binomial distribution method described in Burgasser et al. (2003). For bins with large numbers of stars ($\gtrsim$200), the uncertainties are symmetric and well described by Poisson statistics.[6] These uncertainties are substantially smaller than those reported by W04 due to the larger sample. Figure 3 shows the same data folded across the Galactic plane in order to increase the S/N. The numbers below each data point indicate the number of stars in each bin.

Figures 2 and 3 confirm that the activity fraction decrease is real. In the binned data, the stars that are farther away from the Galactic plane have experienced more dynamical heating and are thus older. As discussed above, the decrease in activity fraction may thus be due to an age-activity relationship. In § 4 we quantify this suggestion using a simple dynamical simulation.

We also investigated how the $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$ ratio changes as a function of vertical height above the Galactic plane (Fig. 4) for the active stars in the sample. The $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$ values have a very large scatter. Because the stars in this sample have nearly the same bolometric luminosity, this scatter represents the scatter in

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[6] Note that the final equation in the Burgasser et al. (2003) appendix describing the Poisson uncertainty has a typographical error: the plus sign should be replaced with a minus sign, and the equation should read $(\epsilon_b^U - \epsilon_b)/\epsilon_b = (\epsilon_b^L - \epsilon_b)/\epsilon_b = (1/n - 1/N)^{1/2}$.

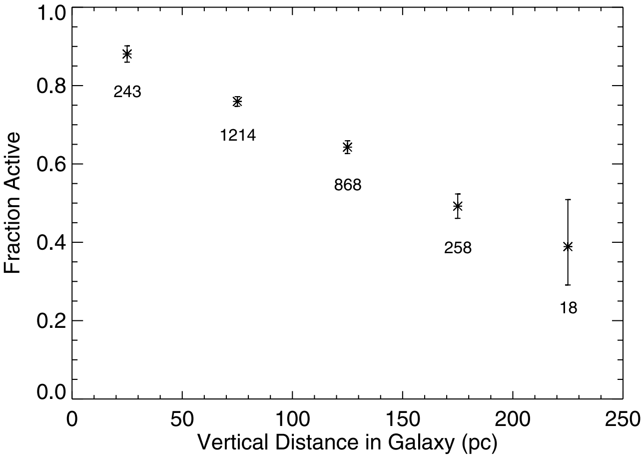

Fig. 3.—Same as Fig. 2, with the stars folded across the Galactic plane in order to obtain a higher S/N result. The values below each symbol represent the number of stars in each bin.

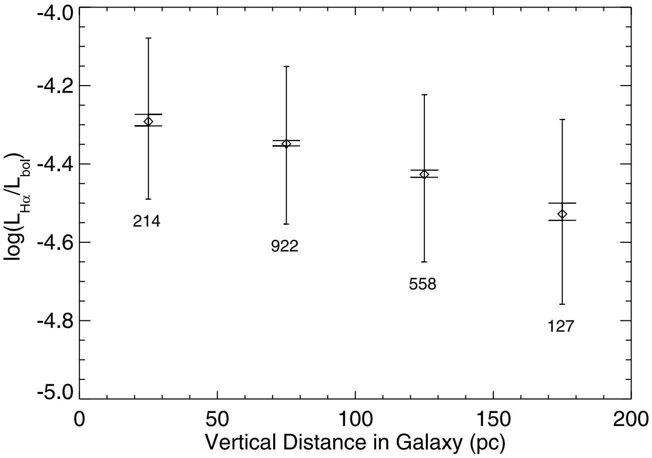

Fig. 5.—Mean $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$ as a function of absolute height above the Galactic plane (in 50 pc bins). The numbers below each symbol indicate the number of active stars in each bin. The short error bars represent the 1 σ spread of the bin, while the long error bars indicate the uncertainty in the mean. The mean does decrease as a function of vertical height, indicating a small but significant decrease in activity with age. In addition, the large spread at all distances and the lack of small $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$ values at close distances argues that activity may suddenly cease when an M dwarf reaches a given age.

Hα luminosity for M7 dwarfs. In order to investigate any trend with distance, we again binned the data and folded them across the Galactic plane. Figure 5 shows the resulting relation. The short error bars indicate the rms scatter of the data in each bin, while the long error bars represent the uncertainty in the mean. There is a small but highly significant decrease in the mean $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$ ratio as a function of vertical distance, which clearly demonstrates that magnetic activity decreases with stellar age. A linear fit to the data revealed a slope of -0.0015 ± 0.00017 dex pc^{-1}, indicating that this result has a 10 σ significance. Does magnetic activity decline continuously or does it eventually go through a rapid decline? The lack of stars with low $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$ ratios at close distances and the presence of high-S/N inactive stars spread over all Galactic heights suggests that M7 dwarfs might eventually shut off rapidly rather than undergoing a perpetually slow decline.

With the space motions derived from the radial velocities, proper motions, and distances, we examined how the vertical velocity dispersion changes as a function of height (Fig. 6). The vertical velocity dispersion was determined in previous studies (e.g., Wielen 1977; Siebert et al. 2003; Bochanski et al. 2005). However, our data represent the largest sample of low-mass dwarfs yet used for Milky Way kinematic analysis and therefore yield the most statistically significant result. We confirm that there is a steady rise in the velocity dispersion as stars are dispersed away from the Galactic plane.

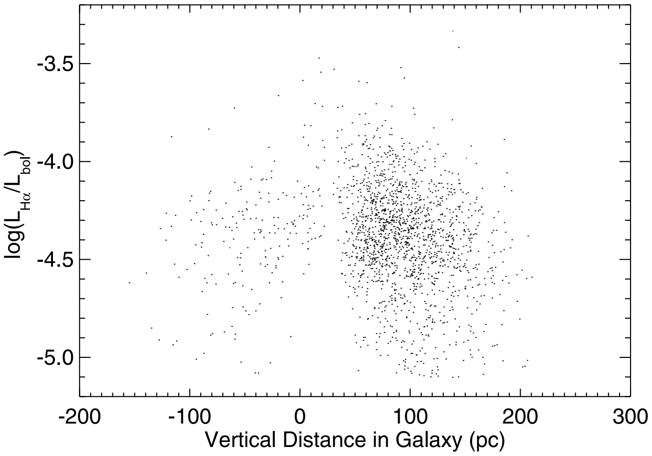

Fig. 4.—$L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$ for all stars in the sample as a function of distance above and below the Galactic plane. Because we investigate only a single spectral type in this study, the L_{bol} value is nearly the same for every star. Therefore, this figure demonstrates the large spread in Hα luminosity at all distances.

4. SIMULATIONS

We proceeded to test the hypothesis that the magnetic activity fraction decrease is caused by a rapid decline in activity in the older, more dynamically heated stars. We developed a simple one-dimensional model to trace the vertical dynamics of stars as a function of time, using the "leapfrog" integration technique (Press et al. 1992) and the vertical Galactic potential from Kuijken & Gilmore (1989) and Siebert et al. (2003) given by

$$\Phi(z) = 2\pi G\left[\Sigma_0\left(\sqrt{z^2 + D^2} - D\right) + \rho_{\mathrm{eff}} z^2\right], \tag{1}$$

where Σ_0 is the total surface mass density, D is the mass scale height, and ρ_{eff} is the halo local effective mass density. We used

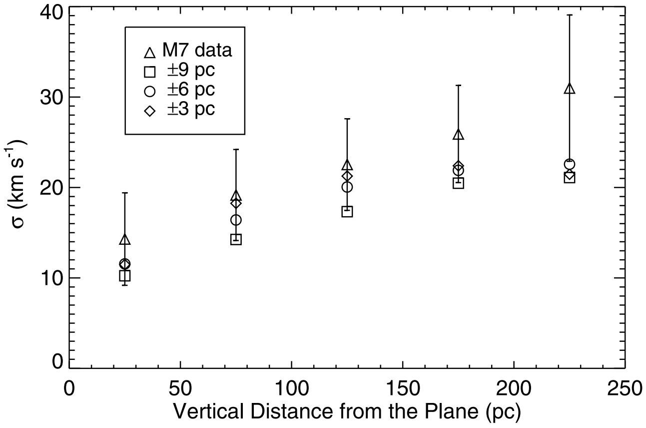

Fig. 6.—Vertical velocity dispersion as a function of distance from the Galactic plane from our simulation (*diamonds, squares, and circles*) and the M7 data (*triangles*). The three best-matched regions of influence (where dynamical heating is important) of ±9 (*squares*), ±6 (*circles*), and ±3 pc (*diamonds*) in our heating simulation are indicated by three different symbols. All of the regions have been modeled to be symmetric about the Galactic plane for simplicity. The resulting dispersions agree with the observational data to within the uncertainties.

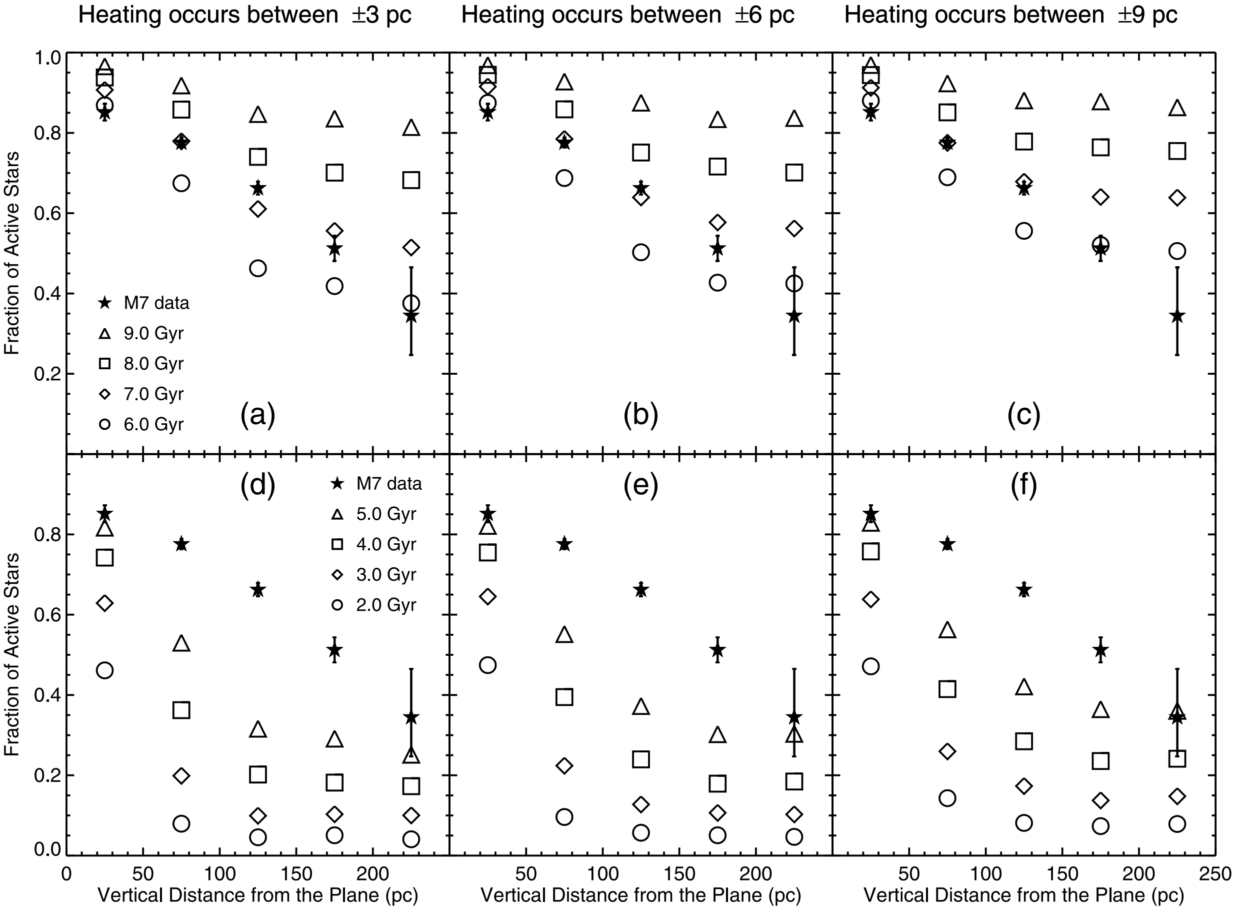

FIG. 7.—Fraction of active stars as a function of absolute vertical distance from the Galactic plane from our simulations and the M7 sample. Each column contains data from a simulation with one of the three regions of influence shown in Fig. 6: ±3 (*a*, *d*), ±6 (*b*, *e*), and ±9 (*c*, *f*). The activity fractions as a function of absolute vertical distance from the Galactic plane are plotted for activity lifetimes of 6, 7, 8, and 9 Gyr (*top panels*) and 2, 3, 4, and 5 Gyr (*bottom panels*). The M7 data (*stars*) are plotted in all six panels. All simulations show a clear decrease in activity as a function of distance from the Galactic plane. The simulations with activity lifetimes between 6 and 7 Gyr and a ±3 pc region of influence best match the data.

the values given in the middle column of Table 3 in the Siebert et al. (2003) study for these quantities.

We assumed a constant star formation rate and injected a new population of 50 stars at the Galactic midplane every 200 Myr for a total simulation time of 10 Gyr. Each new group of stars began with a randomly drawn velocity dispersion of 8 km s^{-1} (Binney et al. 2000) and had a new position and velocity computed every 0.1 Myr. We simulated dynamical heating by altering the velocities (energies) of the stars such that their new velocity dispersions would keep them in agreement with the $t^{0.5}$ relation described above (Wielen 1977; Fuchs et al. 2001; Hänninen & Flynn 2002). Energy was added only when stars were within a given distance from the Galactic plane. These distances were symmetric about the midplane and were varied from ±3 to ±30 pc in intervals of 3 pc. Our simulation tracked the velocity, position, and age of each star in the simulation.

In the Milky Way, molecular clouds and other objects that cause dynamical heating do not lie in a continuous region that is symmetric about the Galactic plane. However, the distances within which energy is added in our simulations can be considered "regions of influence," and they represent the total distance over which a star is subject to dynamical heating during its orbit. Therefore, our simulation reproduces the effect of many finite interactions spread throughout a star's orbit in a manner that is computationally simple.

After the dynamical simulations were complete, we introduced a timescale for magnetic activity to the simulated data. We assigned a range of mean activity lifetimes to every star in all simulations and allowed these lifetimes to vary from 5 to 9 Gyr in 0.5 Gyr intervals. The activity lifetimes were drawn from Gaussian distributions with 1 σ spreads of 1 Gyr. From the resulting data, we can derive activity fractions as a function of vertical distance from the Galactic plane.

Figure 6 shows the vertical velocity dispersion as a function of distance from the Galactic plane from our simulation (*diamonds, squares, and circles*) and the M7 data (*triangles*). The three best-matched regions of influence in our heating simulation are indicated by three different symbols. The observations and simulations agree to within the uncertainties. Figure 6 is included to demonstrate that our simple integrator does indeed produce dynamical outputs that agree with the observations.

The dynamical simulations confirm the plausibility of our hypothesis: dynamical heating and a rapid decrease in magnetic activity at a given age can explain the activity fraction decrease, as shown in Figure 7. Each column contains data from a simulation with one of the three regions of influence shown in Figure 6: ±3 pc (Figs. 7*a* and 7*d*), ±6 pc (Figs. 7*b* and 7*e*), and ±9 pc (Figs. 7*c* and 7*f*). The activity fractions as a function of absolute vertical distance from the Galactic plane are plotted for activity lifetimes of 6, 7, 8, and 9 Gyr (Fig. 7, *top panels*) and 2, 3, 4, and

5 Gyr (*bottom panels*). The M7 data (*stars*) are plotted in all six panels. All simulations show a clear decrease in activity as a function of distance from the Galactic plane. The simulations with activity lifetimes between 6 and 7 Gyr agree remarkably well with the observational data, considering our very simple model. The ±3 pc region of influence is the best match to the data.

These results suggest that the presence of magnetic activity in an M7 dwarf depends on the age of the star. After roughly 6–7 Gyr, M7 dwarfs experience a rapid decrease in their activity such that activity becomes undetectable. Throughout their lifetimes, M7 dwarfs are dynamically heated as they move through the disk. The integral over the region(s) of space in which heating occurs is only a few parsecs but is sufficient to match the observed kinematics.

5. DISCUSSION

Using over 2600 M7 dwarf spectra, we confirm the result of W04, that the activity fraction does decrease as a function of vertical distance from the Galactic plane. A possible explanation for this observation is that activity ceases in older stars and that due to dynamical heating these older stars are, on average, farther away.

Our model simulation using simple dynamical arguments and the assumption that activity ceases at a given stellar age adequately reproduces the observations and validates the feasibility of our hypothesis. A more detailed dynamical simulation should be carried out to aid in the physical interpretation of the observations. The importance of our simulation is simply to demonstrate that our hypothesis is reasonable.

The extrapolation of the simple loglinear fit of the age at which activity ceases versus spectral type (color, mass) derived from a few open clusters in Hawley et al. (2000) would predict a very large age for the M7 dwarfs to cease their activity. Our sample has allowed us to actually probe these late-type dwarfs, which are not accessible in old clusters, and provides the first measured estimate of the time-dependence of their magnetic activity. The investigation of the entire M dwarf sequence by our method will allow us to further refine and extend the relation from the open clusters (S. L. Hawley et al. 2006, in preparation).

The $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$ data show a large scatter that may be due to (1) an intrinsic variation in the activity of a sample of stars or (2) significant variation in the Hα line emission during the lifetime of an individual M7 dwarf. A large sample of low-mass stars with large time baselines is needed to distinguish between these possibilities. If individual stars cannot produce the variation we see in large single-epoch data, then the scatter is likely the intrinsic scatter of the population.

The $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$ data suggest that there is a small but robustly detected decrease in the amplitude of magnetic activity as a star ages, but the large spread at all distances and small decrease of the mean furthers the notion that these stars have some range of magnetic activity during their "active" lifetimes. The mechanism behind this age-activity relation is currently unknown. Future work will statistically explore the spread in $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$ to determine whether the data support the rapid decrease of activity hypothesis.

Our results are important for placing constraints on models of magnetic dynamos in low-mass dwarfs. Many recent studies have investigated the mechanisms controlling magnetic field generation in low-mass stars (e.g., Dobler et al. 2006; Chabrier & Küker 2006; Bercik et al. 2005; Donati et al. 2006). Future dynamo models should include an age dependence in order to match our observations.

Work is under way to expand our M7 analysis to include *all* M dwarf spectral types. S. L. Hawley et al. (2006, in preparation) are using the largest spectroscopic sample of low-mass stars ever assembled (from SDSS Data Release 5) to examine how the activity fractions, space motions, and $L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}$ vary as a function of Galactic height through the M spectral sequence. This will allow us to examine how the dependence of age on activity varies with mass, putting even stronger constraints on dynamo models.

One element that we do not address in this paper is how metallicity varies as a function of Galactic height. The sample size of known M7 subdwarfs is quite small and does not allow for a robust statistical study. However, the Hawley et al. sample will also allow for an exploration of how M dwarf abundances vary with vertical height from the Galactic plane. A metallicity gradient, together with strong age constraints, will provide important information on the chemical evolution of the Galactic disk.

Almost 30 yr have passed since Wielen (1977) used low-mass dwarfs to probe the kinematics and structure of the Milky Way. The advent of large surveys exemplified by SDSS and 2MASS, coupled with the large abundance of low-mass dwarfs, allows us to continue probing the structure of the Galaxy with its smallest and most numerous constituents.

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