ABSTRACT. We use ∼12,000 spectra of ∼3500 magnetically active M0–M9 dwarfs from the Sloan Digital Sky Survey taken at 10–15 minute intervals, together with ∼300 spectra of ∼60 M0–M8 stars obtained hourly with the Hydra multiobject spectrometer, to probe Hα variability on timescales of minutes to weeks. With multiple observations for every star examined, we are able to characterize fluctuations in Hα emission as a function of activity strength and spectral type. Stars with greater magnetic activity (as quantified by \(L_{\text{H}\alpha}/L_{\text{bol}}\)) are found to be less variable at all spectral types. We attribute this result to the stronger level of persistent emission in the high-activity stars, requiring a larger heating event in order to produce measurable variability. We also construct Hα structure functions to constrain the timescale of variability. The more active objects with lower variability exhibit a characteristic timescale longer than 1 hr, likely due to larger, longer lasting heating events, while the less active objects with higher variability have a characteristic timescale shorter than 15 minutes.

Online material: color figures

1. INTRODUCTION

M dwarfs, the least massive and most numerous stars in our Galaxy, provide remote laboratories for observing high-energy magnetic phenomena in stellar atmospheres. The red and dim nature of M dwarfs makes the Hα spectral feature the most accessible tracer of magnetic activity in their convective outer layers (Bopp & Schmitz 1978; Walkowicz & Hawley 2009). M dwarfs with Hα in emission are classified as magnetically active, with a greater fraction of stars showing Hα emission at later spectral types (Hawley et al. 1996; Gizis et al. 2000; West et al. 2011). Magnetic activity is correlated with energetic flaring events that last seconds to hours (Moffett 1974; Kowalski et al. 2010) and photometric brightness increases as large as 8.2 mag in the B band (Almeida et al. 2011). The incidence of Hα emission and large flares decreases for stars farther from the Galactic plane (West et al. 2006, 2008; Kowalski et al. 2009; Hilton et al. 2010; Walkowicz et al. 2011). This is interpreted as an age effect, leading to activity timescales of 1–8 billion years for early-late M dwarfs, respectively.

Variability in quiescent (nonflaring) Hα emission has been attributed to both stellar rotation and M dwarf activity cycles. Bopp & Schmitz (1978) related sequential Hα measurements to orbital phase and suggested that the observed changes were caused by the rotation of localized active regions in and out of view on timescales of days. Activity cycles with periods of a few years have been identified for M dwarfs by Cincunegui et al. (2007) and Buccino et al. (2011) and may affect the observed strength of Hα emission. Although large flares are relatively infrequent events (Hilton 2011), sporadic low-level magnetic field reconnection events (“microflares”) may also contribute to inherent Hα emission variations in active M dwarfs.

There have been some recent investigations of Hα variability on timescales of minutes to days. Gizis et al. (2002) measured the Hα equivalent widths (EWHα) for a sample of more than 600 active M0–M6 dwarfs from the Palomar/Michigan State University (PMSU) survey of nearby stars (Reid et al. 1995) and found that the variation in repeated measurements was near 15% for stars with mean EWHα, \(\langle \text{EWHα} \rangle < 5 \text{ Å}\), while the variability for stars with \(\langle \text{EWHα} \rangle > 5 \text{ Å}\) was in excess of 30%. In their...
study of EWHA variations on later-type stars, Lee et al. (2010) identified significant variability in ~80% of their sample of 43 M4–M8 stars. They found that the majority of variability events had timescales of 30 minutes or longer and that the later-type stars were more variable, as measured by $R(\text{EW}) = \max(\text{EWHA})/\min(\text{EWHA})$. Similarly, Kruse et al. (2010) found an increase in the same metric (which they refer to as $R_{\text{EW}}$) at later spectral types for timescales from 15 minutes to 1 hr in the Sloan Digital Sky Survey (SDSS; York et al. 2000) Data Release 7 (DR7; Abazajian et al. 2009) component spectra. They also noted that $R_{\text{EW}}$ was larger for intermittent sources.

Our analysis uses a set of spectra with exposure times of ~1 hr from the multiobject Hydra spectrograph on the WIYN telescope at Kitt Peak National Observatory, as well as the component spectra from SDSS, to extend the evaluation of H$\alpha$ variability using new metrics and a broader range of timescales. We employ a construct known as the structure function, which is commonly used in quasar variability analyses (e.g., Simonetti et al. 1985; MacLeod et al. 2011), to further constrain the timescales of H$\alpha$ emission variability.

The spectroscopic M dwarf samples we used are detailed in § 2, along with our methods for determining spectral types and measuring H$\alpha$ emission strength. Analysis of H$\alpha$ emission variability with spectral type, activity strength, and timescale is presented in § 3, and we summarize our findings in § 4.

2. DATA

Our data come from two sources that are discussed in detail next: the Hydra instrument on the WIYN telescope (§ 2.1) and the Sloan Digital Sky Survey (§ 2.2). Representative spectra from each sample are displayed in Figure 1. The spectral type distributions of the active M dwarfs in the two samples are shown in Figure 2. These moderate-resolution data sources (Hydra: $R \sim 4000$, SDSS: $R \sim 2000$) are useful for our H$\alpha$ variability analysis because they each provide multiple spectra of the same objects at well-defined time intervals.

Our analysis employs data that were taken over 27 nights between 2002 January and 2008 July as part of the Chandra Multiwavelength Plane Survey (ChaMPlane; Grindlay et al. 2005), which was designed to investigate the fraction of diffuse X-ray emission in the Galactic plane due to unresolved X-ray point sources. Candidate point sources were identified using VR$I$ H$\alpha$ photometry obtained with the mosaic cameras at the Cerro Tololo Inter-American Observatory and the Kitt Peak National Observatory 4 m telescopes. Spectra were obtained with the Hydra multiobject fiber-fed spectrograph on the 3.5 m WIYN telescope for objects with H$\alpha - R < -0.3$, indicating excess H$\alpha$ emission, as well as optically detected objects with corresponding X-ray emission in archival Chandra images.

Although the survey was designed to identify accretion-powered sources such as cataclysmic variables and low-mass X-ray binaries, initial analysis by the ChaMPlane team (Rogel et al. 2006) revealed a sizable population of M dwarfs in the sample, whose spectra and photometry we utilize in this study.

We assigned spectral types to the Hydra data using the Hammer software (Covey et al. 2007) in manual mode, because the flux calibration and signal-to-noise ratio (typically ~10) of the spectra, especially at blue wavelengths, did not allow automatic typing. Each object was visually compared with the Hammer set of M dwarf templates (Bochanski et al. 2007). The resulting spectral types are accurate to within 1–2 types. We verified that the spectral types were broadly consistent with the measured $V - I$ colors of the objects.

The strength of H$\alpha$ emission in each spectrum was quantified by measuring the equivalent width of the line. We followed the procedure described in West et al. (2004) and adopted their definitions for the H$\alpha$ line and continuum regions. Figure 3 identifies these regions for the four Hydra spectra obtained for a representative M4 dwarf. We visually inspected every spectrum in the sample to ensure that the EWHA measurements were not contaminated by cosmic rays or other artificial defects.
Because the equivalent width is measured with respect to the local continuum level, it can be misleading to compare EWHA among stars of different spectral types and, hence, continuum flux near Hα. We therefore computed the ratio of the Hα line luminosity to the bolometric luminosity (L\(\text{H}\alpha/L_{bol}\)) for each object using the \(\chi\) conversion factors of West & Hawley (2008). This quantity represents the continuum-independent activity level, which allows for Hα emission to be compared between stars of different spectral types.

Our analysis was limited to the chromospherically active M dwarfs, identified by the criteria of West et al. (2011) that define detectable Hα emission. Because we intend to use these data in a time-domain analysis, we further restricted the sample to include only those stars with at least three spectra that were identified as active. Our final Hydra sample contains 312 spectra from 62 active M0–M9 dwarfs and allows us to probe Hα emission variability on timescales from 1–3 hr.

2.2. SDSS Spectra

All SDSS spectra are composites of several (typically three–five) spectra with \(\sim\)10–15 minute exposure times. The individual component spectra (with typical signal-to-noise ratio \(\sim\)7) were initially made public as part of the SDSS Data Release 6 (DR6; Adelman-McCarthy et al. 2008). Previous studies have examined the spectral variability of M dwarfs using the individual SDSS spectra from DR6 (Hilton et al. 2010) and DR7 (Kruse et al. 2010); our analysis expands on these efforts. We use the Hilton et al. (2010) sample, which has the spectral type for each object assigned from the composite spectra presented in West et al. (2008). The EWHA measurements for the component spectra followed the same prescription as for the Hydra data. \(L_{\text{H}\alpha}/L_{bol}\) values were obtained from the EWHA calculated for each object, and we verified that they agreed with those measured from the composite spectra given in West et al. (2008). We further restricted our sample to include only the persistently active objects that showed measurable Hα emission in every individual exposure. We note that this reduced the Hilton et al. (2010) active sample by less than 3%.

Our final SDSS sample consists of 11,989 spectra for 3469 active M0–M9 dwarfs and allows us to examine variability on timescales from \(\sim\)15–100 minutes. Nearly 700 stars were observed on multiple days, allowing us to further probe Hα emission changes on timescales of \(\sim\)1–20 days.

3. VARIABILITY ANALYSIS AND RESULTS

We first consider Hα variability as a function of spectral type, comparing our results with variability indicators used in previous analyses (§ 3.1). Our preferred metric for variability is \(\sigma_{\text{EWHA}}/(\text{EWHA})\), and we investigate this metric as a function of activity strength (\(L_{\text{H}\alpha}/L_{bol}\); § 3.2). Finally, we compute structure functions to investigate characteristic timescales in the low- and high-variability subsets of our data (§ 3.3).

3.1. Hα Variability with Spectral Type

Lee et al. (2010) and Kruse et al. (2010) both found that Hα variability increases at later spectral type, using the \(R_{\text{EW}}\) metric. Figure 4 illustrates \(R_{\text{EW}}\) as a function of spectral type for our Hydra and SDSS samples. In agreement with their analyses, we find that the distributions are not symmetric, but have significant extensions to large values of \(R_{\text{EW}}\), with these extensions being more pronounced at later spectral types. However, in our samples the median values (the median is preferred as a statistic instead of the mean for these skewed distributions) scatter around a roughly constant value. This is in contrast to the Kruse et al. (2010) and Lee et al. (2010) results, shown as squares and triangles, respectively. We attribute the difference to the criteria used to identify the active stars. Kruse et al. (2010) and Lee et al. (2010) include stars that they characterize as “intermittently” variable (i.e., only showing Hα emission in a subset of their spectra), and they exclude weakly active stars, which they classify as inactive. These differ from our analysis as a result of their nonuniform equivalent width measurement criteria. Their intermittently variable stars are more prevalent at later types and systematically exhibit larger values of the \(R_{\text{EW}}\) metric. We are able to confidently identify Hα at a much smaller equivalent width, even in late-type M dwarfs, provided the spectra have sufficiently high signal-to-noise ratios (West et al. 2008). Evidently, including these less active, but persistent, objects leads to the approximately flat distribution outlined by the SDSS and Hydra medians in Figure 4.
both the Hydra and SDSS samples. The median 〈\(\alpha\)EWHA〉 for each type is given by the asterisks (SDSS) and filled circles (Hydra). There is no obvious trend in the medians with spectral type. The variability metric decreases with increasing \(\alpha\)EWHA with earlier type stars having relatively smaller equivalent width due to their higher continuum flux near H\(\alpha\), with earlier type stars having relatively smaller equivalent width due to their higher continuum flux. We see that the median \(\sigma\)EWHA is near zero for low (EWHA), rising to \(-0.8\) Å at (EWHA) \(\sim 3\)–6 Å and increasing to \(-1.8\) Å at (EWHA) > 10 Å. Our well-sampled data show a smooth, continuously increasing scatter of \(\sigma\)EWHA with (EWHA) for the median points, in qualitative agreement with the much smaller sample of Gizis et al. (2000). We also note that the maximum value of \(\sigma\)EWHA increases with (EWHA).

As noted previously, the absolute equivalent width values depend on spectral type due to the changing continuum flux near H\(\alpha\), with earlier type stars having relatively smaller equivalent width due to their higher continuum flux. We illustrate this effect in Figure 5b using the fractional variability metric \(\sigma\)EWHA/(EWHA). The skewed nature of the \(\sigma\) distributions at a given (EWHA), evident in Figure 5a (and analogous to the skewed distributions in \(R_{\text{EW}}\) shown in Fig. 4), again leads us to use the median value to characterize \(\sigma\)EWHA/(EWHA) for each (EWHA) bin.

The spectral type dependence of (EWHA) is clearly indicated by the separation of the early (M0–M2, squares), mid (M3–M5, diamonds), and late (M6–M9, crosses) types for the SDSS sample. The median \(\sigma\)EWHA/(EWHA) values for all spectral types are shown as asterisks (SDSS) and filled circles (Hydra). The variability metric decreases with increasing (EWHA) from \(-0.2\) for stars with low EWHA to \(-0.14\) for stars with (EWHA) > 5 Å. A better measure of magnetic activity strength that accounts for the continuum dependence on spectral type is \(L_{\text{bol}}/L_{\text{bol}}\). Figure 6 illustrates the same fractional variability metric \(\sigma\)EWHA/(EWHA) as in Figure 5b versus activity strength. The spectral types are no longer separated; in fact, the three spectral type groups from Figure 5b have shifted horizontally so that they now overlap and form a smooth distribution. It is clear that the underlying variability relationship is not a function of spectral type, but rather of activity strength. However, the median fractional variability (asterisks) decreases with increasing activity from \(-0.3\) at \(\log(L_{\text{bol}}/L_{\text{bol}}) \sim -4.5\) to \(-0.1\) at \(\log(L_{\text{bol}}/L_{\text{bol}}) \sim -3.5\). The median value for the variability metric across the entire sample is 0.16, shown as the dashed line in the figure.
The Hydra data (filled circles) in Figures 5b and 6 show relatively flat distributions that are influenced by small numbers, uneven spectral type sampling, and a bias toward very active stars, especially at early spectral types (due to the $H\alpha - R$ color selection of the targets). Therefore, they are not as useful as the SDSS data for understanding the behavior of the variability metric with activity strength.

The picture we have developed is that highly active stars of all spectral types are relatively less variable than low-activity stars. This only becomes evident when the well-known underlying relationship between activity strength and spectral type is removed, as in Figure 6. Physically, the strong level of persistent emission in the high-activity stars may be due to a large surface coverage of active regions, while the low-activity stars may have a relatively smaller filling factor. An increase in $H\alpha$ emission, for example, due to a new active region appearing on the surface or a magnetic heating episode or microflare in one of the existing active regions, will then manifest as barely visible in the more active star, while it will contribute significant new emission in the less active star. This would naturally explain why the less active stars are relatively more variable.

3.3. Structure Functions and Timescales of $H\alpha$ Variability

Structure functions are often used to explore the variability timescales present in time-resolved observations of quasars (e.g., Simonetti et al. 1985; MacLeod et al. 2011). They represent the change observed between two measurements of some variable quantity, typically broadband flux in the case of quasars, as a function of the time between measurements ($\Delta t$). It is expected that if the observed variability operates on a characteristic timescale ($\tau$), then for $\Delta t < \tau$, the measurements will be correlated. The variability amplitude will increase with greater time separation, as the observations sample more of the total variability range until $\Delta t = \tau$. For $\Delta t > \tau$, the structure function maintains a constant amplitude, as the measurements are uncorrelated and randomly sample the full variability range.

We employ structure functions here to quantify the typical change in the equivalent width measurements for active M dwarf spectra in many bins of time separation, $\Delta t$, and to constrain the characteristic timescale of variability, $\tau$. We divide our samples at the median value of the fractional variability metric in Figure 6 into the less active but more variable stars ($\sigma_{\text{EWHA}}/(\text{EWHA}) > 0.16$) and the more active but less variable stars ($\sigma_{\text{EWHA}}/(\text{EWHA}) < 0.16$). We then calculate the change in $H\alpha$ emission as a fraction of the mean value, $\Delta\text{EWHA}/(\text{EWHA})$, between every pair of repeated measurements for the same M dwarf.

To illustrate how the structure function amplitude is calculated, the distributions for three SDSS time bins from the less variable (more active) subsample are presented in Figure 7. Each time bin (the $\Delta t$ range indicated in the figure) contributes one point on the structure function. The typical change between measurements for a given $\Delta t$ bin is taken as the rms of the $\Delta\text{EWHA}/(\text{EWHA})$ distribution, normalized by the number of samples in that time bin. This accounts for the uneven sampling of time separations in our data sets. The normalized rms values for these three bins increase from 0.13 to 0.16 with increasing $\Delta t$. The SDSS structure functions were constructed from similar normalized rms values that were calculated for 14 time bins spanning the entire range of $\Delta t$ sampled by our data. The time bins were chosen to provide good statistics at short $\Delta t$ intervals (15 minutes to 2 hr), where there are many observations, and to cluster around typical $\Delta t$ values for longer intervals (e.g., one day, several days). The Hydra structure functions were only computed for a few time intervals, reflecting the approximately hourly cadence of the observations.

![Fig. 6.—The same medians of the fractional variability metric ($\sigma_{\text{EWHA}}/(\text{EWHA})$) from Fig. 5b are shown as a function of activity strength $\log \frac{L_{\text{rad}}}{L_{\text{bol}}}$. The symbols are the same as in Fig. 5b. The downward trend in the SDSS data shows that variability decreases in more active M dwarfs, regardless of spectral type. The Hydra data do not show a coherent trend, which we attribute to poor sampling and a bias toward very active, early-type stars. See the electronic edition of the PASP for a color version of this figure.](image1)

![Fig. 7.—Three time bins from the structure function of the low-variability SDSS sources. Each point on the structure function in Fig. 8 is a normalized rms (vertical dashed lines) calculated from a distribution of $\Delta\text{EWHA}/(\text{EWHA})$ that is populated by pairs of observations separated by a specific range of time, $\Delta t$ (given in hours at the top of each panel).](image2)
Figure 8a illustrates the SDSS (asterisks) and Hydra (filled circles) structure functions for the high-variability sample \((σ_{EWHA}/EWHA > 0.16)\), and Figure 8b gives the structure functions for the low-variability sample \((σ_{EWHA}/EWHA < 0.16)\). The timescales range from 15 minutes to 20 days. The irregular binning in \(Δt\) reflects the nonuniform separations of the measurements in time due to the sampling cadences of the surveys. We also require that the shortest time bins (\(Δt < 2\) hr) in the SDSS structure function contain at least 150 measurement pairs, in order to obtain well-defined normalized rms values (see Fig. 7). At larger time separations, the sample sizes are smaller and the error bars on the structure function amplitudes are correspondingly larger.

The low-variability structure function for the SDSS sample in Figure 8b shows a significant trend with time, indicating increasing variability up to a timescale of at least 1 hr. The plateau at timescales shorter than \(Δt \sim 0.4\) hr suggests that measurement uncertainties may dominate any variability amplitude effects below that time separation.

The high-variability structure function (Fig. 8a), on the other hand, shows a flat distribution at all times for the SDSS sample. The structure function amplitude is much larger, which is indicative of the higher level of variability seen in this sample. The measurement uncertainties are much less than the detected rms (structure function amplitude), indicating that the variability timescale is shorter than our smallest time-separation bin, \(\sim 15\) minutes.

While sparsely sampled, the Hydra data reinforce this interpretation. In Figure 8a, both the SDSS and Hydra exposure times are longer than the underlying characteristic timescale for the high-variability data, and therefore all measurement pairs are randomly sampling the intrinsic equivalent width variations, leading to flat structure function amplitudes. The longer exposure time for the Hydra data (1 hr, compared with 10–15 minutes for SDSS) damps the stochastic variations between exposures, and the amplitude of the Hydra structure function is correspondingly smaller. The low-variability Hydra sample in Figure 8b has a characteristic timescale that is apparently comparable with the exposure time, and thus the structure function amplitude is flat over the 1–3 hr time separations that are sampled. In this case, the structure function amplitude is consistent between the SDSS and Hydra samples.

The increase in variability amplitude with time seen in our low-variability (high-activity) sample is reminiscent of the Lee et al. (2010) result that there was a much larger number of \(H\) emission events that lasted at least 30 minutes compared with the number of shorter events they observed. Their sample was primarily composed of very active stars, which is comparable with this subset of our data.

Following the discussion in § 3.2, we interpret the timescale results as follows. The low-variability (high-activity) stars are covered with spots, so that small variations are not easily visible against the high background. In order to see a noticeable variation, a rather significant event must occur. Since higher-energy events are known to last longer (e.g., Lacy et al. 1976; Hawley & Pettersen 1991), this leads to a longer timescale for events that are strong enough to be detected above the persistent activity. For the high-variability (low-activity) stars, small events will cause a noticeable change, and these occur on short timescales, below the \(\sim 15\) minute limit of our sampling cadence.

### 4. SUMMARY

We used two spectroscopic samples of active M dwarfs to examine \(H\) emission variability on timescales from minutes to weeks.

We found that the \(H\) variability measured using the \(R_{EW}\) metric remains relatively constant as a function of spectral type, in contrast to previous results. However, using our fractional variability metric \((σ_{EWHA}/EWHA)\), we showed that the higher-variability stars have relatively low activity strength \((L_{H}/L_*)\) and that, conversely, the low-activity stars have high activity strength. This naturally leads to an apparent dependence on spectral type, because the later-type stars typically have lower activity strength. We speculated that the physical reason for the higher variability in the low-activity stars is that small changes in \(H\) emission, e.g., due to small-scale flaring or the appearance of a new active region on the stellar surface, would have a relatively larger effect on the less active stars.

We investigated the timescales of \(H\) emission variability using structure functions. The observed \(H\) variations for low-variability stars \((σ_{EWHA}/EWHA < 0.16)\) occur on a timescale longer than 1 hr, while the high-variability M dwarfs exhibit a timescale that is shorter than our sampling time of \(\sim 15\) minutes. Neither the low- nor high-variability samples show significant
changes in the structure function on timescales longer than a day. We speculated that the low-variability sample, which is mainly composed of the higher activity strength stars, requires more energetic and hence longer-lived emission events in order to be detected above the strong persistent surface activity, leading to a longer characteristic variability timescale.

Better time resolution in spectroscopic M dwarf monitoring, as well as a wider and better-sampled range of time separations, will allow for a more accurate determination of the timescales of Hα variability in low-mass dwarfs and may lead to a better understanding of the physical mechanisms that cause these changes.

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