1. INTRODUCTION

M dwarfs are notorious for dramatic flares, presumably caused by magnetic reconnection in their atmospheres. Weaker analogs of these flares are present on the Sun, where the surface magnetic field is thought to be powered by the rotationally induced shear between the radiative and convective layers of the Sun (Parker 1955). For fully convective M dwarfs (spectral types M3 and later; Chabrier & Baraffe 1997), strong magnetic fields are created and sustained solely through turbulence and rotation within the star (e.g., Browning 2008). The dynamo powering the magnetic fields which result in flares on these M dwarfs is not fully understood, but additional observations constraining the chromospheric heating are essential to a coherent picture relating stellar magnetic fields to flares.

The atmospheric heating during a flare results in emission from many wavelength regimes, and flares have been well observed in the X-ray (e.g., Osten et al. 2010), ultraviolet (e.g., Robinson et al. 2005; Hawley et al. 2007), optical (e.g., Kowalski et al. 2009; Walkowicz et al. 2011), and radio (e.g., Stepanov et al. 2001; Osten & Bastian 2008). The combination of observations at these different wavelengths, especially when obtained as part of multi-wavelength flare monitoring campaigns, has informed our interpretation of the physics underlying these dramatic emission events (e.g., Hawley et al. 2003; Osten et al. 2005). However, to date there have been no concerted efforts to observe infrared emission lines from flaring stars. Quiescent M dwarfs are particularly bright in the near-infrared portion of the spectrum, so emission from the hydrogen Paschen and Brackett series and the He I λ10830 transition are both easily observable and essential to probing different atmospheric heights. These infrared emission lines are particularly useful for examining accretion in T Tauri stars (e.g., Bary et al. 2008; Vacca & Sandell 2011).

In quiescent (not flaring) active M stars, high-resolution (R > 20,000) spectra have shown weak absorption from Pβ in AU Mic (Short & Doyle 1998); Fe was also seen in absorption in six out of ten active M dwarfs (Houdebine et al. 2009). Emission from higher-order Paschen lines has only been detected in a few serendipitous observations at the far red end of optical spectra. The first occurred during a survey to classify photometrically selected late-M and L dwarfs. Liebert et al. (1999) observed Paschen emission (P6–P11) between 8800 Å and 10500 Å in an R ~ 4300 spectrum of the M9.5 dwarf 2MASSW J01490904+295613. The flare also showed a variety of optical emission lines, but had no evidence of continuum emission. Schmidt et al. (2007) subsequently observed Paschen emission lines in an R ~ 2000 spectrum of the M7 dwarf 2MASS J1028404–143843. The flaring spectrum included strong continuum enhancement of the entire spectrum blueward of 9200 Å in addition to many emission lines. P8–P11 were again identified, with equivalent widths (EWs) of 2–5 Å. For both of these observations, there was no corresponding photometry, which prohibited the characterization of the overall strength and duration of the flare.

Fuhrmeister et al. (2008) observed P6–P11 on the M5.5 dwarf CN Leo during a large-amplitude flare with a total duration of about 45 minutes. Their data included R ~ 40,000 spectra over the range 3000–10500 Å. Line strengths were not given for the Paschen lines, but inspection of the three consecutive 100 s exposures near the peak of the flare shows a decay in line strength. Fuhrmeister et al. (2010) used one-dimensional atmosphere models to examine the emission from the flare, finding that a single model can reproduce most, but not all, flare emission lines.

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An unexplored region of the spectrum during M dwarf flares, both in observations and modeling, is the 1.0–2.5 μm range, which contains the lower-order Paschen lines, higher-order Brackett and Pfund lines, and He I 10830. We report on the results of our campaign to observe active M dwarfs in this wavelength regime with simultaneous photometric monitoring. The data include three flares with infrared line emission; observations of the strongest flare also include blue optical spectra. Using these data, we quantify the duty cycle for infrared spectra. Individual flares are examined in Section 4 together with our atmospheric models that produce infrared line emission and characterize a flare, we need at least one background star. Photometry for all of the nights was obtained using FlareCam on the ARC 3.5 m telescope at APO. Exposure times were 2–4 s for the A0 calibrator star every ∼40 minutes in order to correct for the changing telluric absorption over the course of the night. Our typical exposure times were 2–4 s for AD Leo, EV Lac, and YZ CMi, and 30 s for VB 8.

The data were reduced using a version of SpexTool modified to work with ARC 3.5 m TripleSpec data (Cushing et al. 2004). We constructed telluric correction spectra from our A0 standards using the routine included in SpexTool (Vacca et al. 2003), but modified the remaining post-processing routines to automatically process each spectrum instead of using the GUI interface provided. Although the formal residuals of our wavelength solution were 0.5–1 μm, the curved, tilted orders of the spectra impose additional systematic effects in the wavelength calibration. We detected Pβ, Pδ, Pγ, Brγ, and He I 10830 during the most energetic flare observed. No higher-order Brackett or Pfund emission was detected in any of our spectra. We measured the EWs using regions defined individually for each line in order to include all observed flux; for Pβ, Pδ, Pγ, and He I 10830, these were 10–20 Å wide (6–12 pixels; 0.001–0.002 μm) and for Brγ the line region was 40 Å wide (14 pixels; 0.004 μm). Continuum regions were defined as ±0.01 μm on either side of each line. Quiet and flare profiles for the five lines are shown with the regions used for line measurements in Figure 1. The spectrum surrounding and underlying each of the emission lines contains many other molecular and atomic features so the EWs of the emission lines are not zero even in quiescence. The EW

### Table 1

| Name      | ST   | J     | K     | t_{obs} (h:m) | N_{flare} | t_{flare} (h:m) | N_{flare IR} | t_{flare IR} (h:m) | Frac IR |
|-----------|------|-------|-------|---------------|-----------|-----------------|--------------|------------------|---------|
| YZ CMi    | M4.5 | 6.58 ± 0.02 | 5.70 ± 0.02 | 16:36         | 8         | 1:55            | 1            | 0.08             | 0.008   |
| AD Leo    | M3   | 5.45 ± 0.02 | 4.59 ± 0.02 | 12:18         | 1         | 0.31            | 0            | 0.00             | 0       |
| EV Lac    | M3.5 | 6.11 ± 0.03 | 5.30 ± 0.02 | 15:21         | 6         | 3:56            | 2            | 1:14             | 0.081   |
| VB 8      | M7   | 9.78 ± 0.03 | 8.82 ± 0.02 | 4:37          | 1         | 0.15            | 0            | 0.00             | 0       |

| M3–M4.5    |      |       |       | 44:15         | 15        | 6:22            | 3            | 1.22             | 0.031   |
| Total      |      |       |       | 48:52         | 16        | 6:38            | 3            | 1.22             | 0.028   |

**Notes.** The total time observed is given in Column 5 (t_{obs}); the total time each object spent in flare is given in Column 7 (t_{flare}), and the time with observed infrared line emission is given in Column 9 (t_{flare IR}; see Figures 3, 5, and 6). The last column gives the fraction of time each object spent with infrared line emission.

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### 2. OBSERVATIONS

Our targets include three well-known mid-M flare stars, AD Leo, EV Lac, and YZ CMi, in addition to one active late-M dwarf, VB 8. Magnitudes, coordinates, and the duration of our observations for each target are given in Table 1. To both detect IR emission and characterize a flare, we need at least one band of optical photometry, but some nights include additional data. The targets, times observed, and instruments used each night are detailed in Table 2.

#### 2.1. Flare-cam on the ARCSAT 0.5 m

Photometry for all of the nights was obtained using Flare-cam on the Astrophysical Research Consortium Small Aperture Telescope (ARCSAT). ARCSAT was formerly used as the photometric calibrated telescope for the Sloan Digital Sky Survey (York et al. 2000; Tucker et al. 2006). Its location at Apache Point Observatory (APO) makes it an ideal telescope for obtaining simultaneous data with the ARC 3.5 m telescope, which we used for our infrared spectroscopy (see Section 2.3). Flare-cam is equipped with ugrι filters, and the CCD is optimized for observing flare stars because of its good blue response and fast readout (Hilton 2011). Exposure times and filters are given in Table 2.

The data were reduced using standard IRAF routines combined with a custom python code that tracked the change in each star’s position over the course of the night. The magnitudes were calibrated using differential photometry with respect to the brightest stars in the image. See Hilton (2011) for more details on the photometric reductions.

#### 2.2. NMSU 1 m

For four of the eleven nights of observations listed in Table 2, we also obtained U-band photometry using the NMSU 1 m, a robotically operated telescope located at APO (Holtzman et al. 2010). Typical exposure times were 4–10 s, and readout was 10 s. The reductions were performed using an automated pipeline which measured the magnitude of the flare star with respect to several background stars.

#### 2.3. TripleSpec on the ARC 3.5 m

Infrared spectra were obtained with the TripleSpec instrument on the ARC 3.5 m telescope at APO. TripleSpec is a cross-dispersed near-infrared spectrograph that covers 0.95–2.45 μm (Wilson et al. 2004). We used the J″, I′, I′′, and H′′ filters, and the time with observed infrared line emission is given in Column 9 (t_{flare IR}; see Figures 3, 5, and 6). The last column gives the fraction of time each object spent with infrared line emission.
measured in the quiescent spectrum is subtracted from each flare measurement.

We could not determine absolute line fluxes directly from individual TripleSpec spectra because the observed flux in each spectrum varies due to the movement of the star on and off the slit during the nod pattern. We used a method similar to the $\chi$ factor of Walkowicz et al. (2004) to calculate absolute line flux by multiplying measured EWs (which do not depend on the continuum level) by a calibrated continuum flux. Continuum fluxes were obtained from a quiet, co-added, high signal-to-noise ($S/N$) spectrum of each star normalized to Two Micron All Sky Survey (2MASS) photometry using 2MASS filter curves (Cohen et al. 2003; Skrutskie et al. 2006). While this method would not be feasible in the UV and optical due to white-light emission, continuum enhancement during flares is negligible in the $JHK_s$ passbands. Davenport et al. (2012) use a flare continuum model on an M3 star to predict that a flare with $\Delta V = 4$ mag would produce a $\Delta J < 10$ mmag peak, and Tofflemire et al. (2012) report no broadband ($J, H, K_s$) continuum enhancements above a level of 5–8 mmag during flares having similar total energy as reported here. The variations detected by Tofflemire et al. (2012) and Davenport et al. (2012) are smaller than the formal uncertainty quoted with the 2MASS magnitudes (20–30 mmag), so we assume that the variation between the published 2MASS magnitudes and the magnitudes of the M dwarfs during our observing was negligible.
2.4. DAO 1.8 m

For two nights, we used the DAO 1.8 m telescope with the STIRE5 CCD and spectrograph to observe EV Lac during a coordinated campaign with the telescopes at APO. Our setup resulted in a spectral resolution of $R \sim 750$ and wavelength coverage from 3550 Å to 4700 Å. We measured CaII K, HeI λ4471, and the hydrogen Balmer series Hγ and Hδ. Exposure times for EV Lac ranged from 60 to 420 s. Due to these relatively long integration times, additional cosmic-ray cleaning was performed with the LACOSMIC utility (van Dokkum 2001).

The spectra were wavelength-calibrated with an FeAr lamp and flux-calibrated using data from the standard star G191B2B, then spectrophotometrically calibrated by normalizing to the simultaneous $U$-band data. EWs are not useful for blue flare spectra because of the changes in the surrounding continuum flux during the flare. Instead, we measured absolute line fluxes directly from the data. The values we use during the flare have the quiet line flux subtracted.

3. IDENTIFYING FLARES

Flares are most easily seen at blue and ultraviolet wavelengths, where the hot, white-light continuum emission from the flare is in high contrast to the small amount of flux emitted from cool M dwarf photospheres (Lacy et al. 1976; Hawley & Pettersen 1991). To identify as many flares as possible, we used the bluest band of photometry available. This was typically $u$, but for some nights only $U$ was available, and VB 8 was too faint to observe in $U$ or $u$, so we used $g$-band data. The band used to identify flares for each set of observations is given in Table 2.

Photometrically, flares are observed as excursions above the mean quiescent value of the star’s flux, which can be any size or shape. Realistically, flare detection must take into account small variations in the continuum caused by observational effects and so a minimum duration and energy above the observed quiescent value is required. To identify individual flares, we used the custom IDL code discussed in Hilton (2011), which selects peaks that have at least three consecutive epochs more than three standard deviations above the local quiescent light curve. At least one of those epochs must be 5σ above quiescence. We reviewed each flare by eye to confirm that the deviations from the mean were not caused by bad photometry. Over the course of 48.9 hr of observations on four different stars, we observed a total of 16 flares, which are listed per star in Table 1 and per night in Table 2. Figure 2 shows the energy and peak magnitude of each flare.
To identify flares which had associated IR line emission, we examined the measured EWs of Pβ and He I λ10830 as a function of time during the flare. We found that the three most energetic flares, which occurred on EV Lac on UT 2009 October 27 and UT 2010 November 27, and on YZ CMi on UT 2011 February 14, each showed infrared emission lines. These flares are discussed in detail in Section 4.1.

4. CHARACTERIZING INFRARED FLARES

4.1. Individual Flares

2009 October 27 flare on EV Lac. We were observing with all four instruments during the most energetic event, a ∆υ = 4.02 mag flare on EV Lac on UT 2009 October 27. The light curves for our observations are shown in Figure 3. The photometry (in U, u, and g bands) exhibits a typical flare light curve with a fast rise and exponential decay. The u-band flare emission lasted 1.68 hr and released a total energy of $3.9 \times 10^{32}$ erg.

The combination of optical (DAO) and infrared (TripleSpec) spectroscopy allows us to examine a total of nine emission lines—Hγ, Hδ, He I λ4471, and Ca II K in the UV/blue part of the spectrum, and Pγ, Pδ, Pβ, Brγ, and He I λ10830 in the infrared. Figure 4 shows the light curve of each emission line normalized to its value at $t = 4.97$ hr (the peak of u-band emission), and the ratio of each line to Hγ for comparison of their evolution during the flare.

The light curves for Hγ, Hδ, and He I λ4471 have a fast-rise exponential-decay shape similar to the photometry. Pγ and Pδ show a similar fast rise, but their decay is slower than the Balmer series lines. The Pβ and Ca II K emission both peak after the other Paschen and Balmer series lines, and exhibit an even slower decay after their late peaks. Brγ is similar to Pβ and Ca II K in its late peak, but seems to decay faster than any other line. This may be an observational effect, as it is by far the weakest line detected. Without a stronger detection, we assume that its
ratio to the Paschen lines is constant throughout the flare. The \( \text{He} \lambda 10830 \) emission shows a shape distinct from the rest of the lines—it remains nearly at its peak flux for 0.8 hr, approximately half of the duration of the flare in \( u \) band.

The slow decay during the gradual phase is a well-known property of \( \text{Ca} \Pi \) (e.g., Bopp & Moffett 1973; Hawley & Pettersen 1991; Fuhrmeister et al. 2008), but in this flare \( \text{He} \lambda 10830 \) emission traces a region that remains heated for an even longer portion of the gradual phase than \( \text{Ca} \Pi \). This could be due to the Neupert effect, where the line responds to the total cumulative flare heating for which the time integral of the \( U \) band (white-light emission) is often used as a proxy (Hawley et al. 1995; Osten et al. 2005). Section 5 describes our efforts to model the emission lines from this flare.

2010 November 27 Flare on EV Lac. We observed another flare with infrared line emission on EV Lac on UT 2010 November 27. The flare peaked at \( \Delta U = 1.68 \), and over the course of \( t = 1.30 \) hr it emitted \( 5.5 \times 10^{31} \) erg in the \( u \) band. We observed with both ARCSAT and TripleSpec during the flare, and have photometry in \( g \) and \( r \) band in addition to the \( u \)-band data. The photometry and the line flux light curves for \( \text{P} \beta \), \( \text{P} \gamma \), and \( \text{He} \lambda 10830 \) are shown in Figure 5. There was no discernible emission in \( \text{P} \delta \) and \( \text{Br} \gamma \).

This peculiarly shaped flare contains three separate peaks in the \( u \)-band photometry. After the first and third peak, the flux seems to decay exponentially, but after the middle peak there is a gentle rise in the \( u \)-band flux. TripleSpec was taking observations of a standard star during the first peak of the flare, so it is unknown if the emission lines showed the same fast rise and exponential decay as the first photometric peak. The rise in \( \text{P} \beta \) and \( \text{P} \gamma \) line emission before and after the standard star suggests that those lines showed some emission between the first and second peaks of the flare. An observed increase in infrared line emission occurred \(~0.2\) hr after the second peak in the \( u \)-band photometry, tracing a gentle rise and decay.

The shape of this flare is very different than that of the UT 2009 October 27 flare on EV Lac, and the relative line strengths are also different. In the previous flare, \( \text{P} \beta \), \( \text{P} \gamma \), and \( \text{He} \lambda 10830 \) emitted nearly the same peak flux. In this flare, \( \text{He} \lambda 10830 \) peaked at twice the strength of the \( \text{P} \beta \) and \( \text{P} \gamma \) lines, indicating a different pattern of atmospheric heating during the two flares.

2011 February 14 flare on YZ CMi. On UT 2011 February 14, we observed a \( \Delta U = 1.38 \) flare on YZ CMi with the NMSU 1 m, ARCSAT, and TripleSpec. The flare lasted for \( t = 0.5 \) hr and released a total \( U \)-band energy of \( 4.4 \times 10^{31} \) erg. Figure 6 shows the \( U \)-, \( g \)-, and \( r \)-band light curves (\( i \)-band was also observed but showed no change during the flare) and line fluxes from \( \text{P} \beta \), \( \text{P} \gamma \), and \( \text{He} \lambda 10803 \). This is the lowest energy flare with any evidence of IR line emission, and the measured EWs were small (0.05–0.2 Å), which provides a lower limit on the observability of IR line emission. With these small EWs, it is difficult to compare the strengths of the emission lines; they are all the same strength within the uncertainties.

The \( U \)-band light curve shows a fast-rise exponential-decay shape with a precursor event 0.1 hr before the main peak. The IR emission does not show the precursor or the initial rise of the photometry. However, the co-added infrared measurements have an effective time resolution of 2.5 minutes (due to the
inclusion of time spent executing the nod pattern and readout), which is insufficient to resolve those features.

4.2. How Often Does IR Line Emission Occur?

In order to determine the expected rate, or duty cycle, of infrared line emission, we first defined detectable emission as approximately 1σ above the mean quiescent level. The length of time with detectable emission is shown for each flare as the red horizontal line on the $P\beta$ light curve in Figures 3, 5, and 6 and given in Table 1. The total time spent in emission for all three flares observed is 1.4 hr (out of 48.9 possible hours), which corresponds to an IR flare emission duty cycle of 2.8%. Excluding VB 8, we calculate an IR flare emission duty cycle of 3.1% (of 44.3 hr) for active mid-M dwarfs.

We can also place a limit on the duty cycle using the flare frequency distributions from Hilton (2011), which give the number of $u$-band flares per unit time for each flare energy. The $u$- and $U$-band energies of the flares with accompanying infrared emission are all above $3 \times 10^{31}$ erg, corresponding to a flare frequency <0.1 hr$^{-1}$. Multiplying this emission time per flare by the flares per hour gives a duty cycle of <4.6%, in agreement with our independent estimate. A duty cycle of 2.8%–4.6% represents an upper limit on detectable emission at this S/N and resolution, as our criterion requires only a small detection in the brightest line.

5. ATMOSPHERIC STRUCTURE

We used the static NLTE radiative transfer code RH (Uitenbroek 2001) to generate model spectra to compare with...
the emission lines observed in the UT 2009 October 27 flare on EV Lac. We calculated model spectra based on one-dimensional atmospheres, using a 20-level hydrogen atom, a 20-level calcium atom, and a 25-level helium atom. The multi-level atoms were required to generate the lines observed, while the simplification to a one-dimensional atmosphere allowed us to examine a larger range of chromospheric structures without the computationally intensive calculations required by a detailed treatment of flare physics (e.g., Allred et al. 2006).

For a starting atmosphere, we used a Nextgen photospheric model from a $T = 3200$ K solar metallicity dwarf (Hauschildt et al. 1999) and the corona of the pre-flare M dwarf atmosphere model of Allred et al. (2006). Similar to Hawley & Fisher (1992), Christian et al. (2003), and Fuhrmeister et al. (2010), we used chromospheres with a linear temperature rise in log column mass (log(col mass)) to connect the photosphere and corona. The linear temperature rise is a simplification of the actual chromospheric structure during a flare, but it is useful for an initial investigation of the temperatures required to generate emission lines at each atmospheric height. To produce a suite of model atmospheres, we varied the column mass of the transition region (log(col mass)$_{TR}$), the column mass of the temperature minimum region (log(col mass)$_{T_{min}}$), and the temperature of the chromosphere at the bottom of the transition region ($T_{TR}$).

Figure 7 shows the temperature structure of a representative subset of the resulting atmospheres and illustrates the three quantities we varied.

Following Walkowicz (2008), we adopted our initial ranges for $T_{TR}$, log(col mass)$_{TR}$, and log(col mass)$_{T_{min}}$ from previous quiescent and flaring M dwarf chromosphere models (Hawley & Fisher 1992; Mauas & Falchi 1994; Houdebine & Stempels 1997; Short & Doyle 1998a; Walkowicz et al. 2008; Fuhrmeister et al. 2010). Table 3 shows the range of parameters adopted for each of these three quantities, which differ from previous parameter ranges only in $T_{TR}$. Previous model atmospheres have relatively constant $T_{TR} \approx 10000$ K, but our initial models with a range of $T_{TR} = 10000$ K–20000 K underproduced Paschen emission relative to Balmer emission, and showed a trend of increasing Paschen emission with greater $T_{TR}$. We increased the temperature of our hottest models to $T_{TR} = 30000$ K in order to generate relatively more Paschen emission. Although $T_{TR}$ extends to hotter temperatures, it is consistent with results from the radiative hydrodynamic simulations from Allred et al. (2006), which show that material at the base of the transition region can be heated up to $T = 10^6$ K.

Comparing the strengths of the modeled lines to each other provides strong constraints on our suite of model atmospheres. The line flux ratios with respect to the $H\gamma$ line flux for the best models are shown compared to the median and range of observed line flux ratios in Figure 8. In general, a deeper $T_{min}$ (at log(col mass) = 0 or −1), a deeper transition region (at log(col mass) = −3.5 or −4.5), and a hotter chromosphere (with $T_{TR} = 25000$ K or 30000 K) better reproduce the line flux ratios observed during the flare. The line formation regions (where the contribution function for each line is greater than 25% of its peak value) for one model are shown in Figure 9.

Most of the lines are produced over regions that include the outer portion of the chromosphere, at log(col mass) = −3.5 and $T = 25000$ K. $H\gamma$, the strongest emission line we observed, is formed over the smallest portion of the chromosphere, with its highest temperature at $T = 20000$ K. He I $\lambda 4471$ and He I $\lambda 10830$ form over slightly different regions of the atmosphere, with He I $\lambda 10830$ tracing slightly higher temperatures.

During the flare observations, the ratio of H$\delta$ to $H\gamma$ is relatively constant. H$\delta$ is slightly overproduced in the models compared to observations, but is similar in each of the models. He I $\lambda 4471$ emission is weak (with a ratio to $H\gamma$ of ~0.1–0.3) in both the models and the observations. The ratios of the Paschen series lines and Brackett $\gamma$ to each other are relatively constant throughout the flare, and those ratios are well produced in every atmospheric structure. The ratio of the Paschen lines and Brackett $\gamma$ to $H\gamma$, however, is matched only in the models with a log(col mass)$_{T_{min}} = 0$. Because these lines are sensitive to the hottest regions of the chromosphere, the advantage of the log(col mass)$_{T_{min}} = 0$ is likely an increased amount of material at temperatures near $T = 20000$ K due to a shallower slope in the chromosphere.

The ratio of Ca II K to $H\gamma$ and to the other hydrogen series lines is best produced in the models with the deepest $T_{min}$, a deep transition region (log(col mass)$_{TR}$ = −3.5 or −4.5), and a hot $T_{TR} = 25000$ K or 30000 K. In all other models, Ca II K is underproduced relative to the Paschen series lines. As shown in Figure 9, the Ca II K emission in the best-fit model is formed over a larger range of log(col mass) than any other line. The production of Ca II K in a region that includes the upper chromosphere is unusual compared to previous results; typically, Ca II K emission during a flare is thought to last longer because it is a lower temperature line (Houdebine 2003; Crespo-Chacón et al. 2006). Our cooler atmospheres, where Ca II K emission is formed only in lower temperature regions, do not produce enough Ca II K emission relative to Paschen series emission to match our observations.

He I $\lambda 10830$ is underproduced in nearly every model. During the flare, its observed ratio compared to $H\gamma$ increases from 0.1

| Parameter                | Range          | Best             |
|--------------------------|----------------|------------------|
| log(col mass)$_{TR}$     | −5.5 to −3.5   | −5.5 to −4.5     |
| log(col mass)$_{T_{min}}$| −3 to 0        | 0                |
| $T_{TR}$                 | 10000 K to 30000 K | 25000 K to 30000 K |
to 0.5, while all our models show line flux ratios of 0.1 or less. This mismatch is apparently worse in one of the other two flares observed; as discussed in Section 4, He I λ10830 is stronger compared to Pβ and Pγ (the two other lines observed) in the UT 2010 November 27 flare on EV Lac. Simply raising the T_{TR} in our models produces too much Ca II K but no additional He I λ10830. In the Sun and similar stars, He I λ10830 emission is produced in the upper chromosphere during flares as a result of helium ionization via backwarming from coronal UV flux (Mauas et al. 2005; Sanz-Forcada & Dupree 2008). A similar process could be leading to the He I λ10830 emission during M dwarf flares, but the details of backwarming from coronal emission are not yet fully implemented in the RH atmosphere code.

While one-dimensional atmosphere models can match the line flux ratios of most of the lines as a sequence of static snapshots, they cannot reproduce the time evolution of the flare. In our observations, Ca II K, the Paschen lines, Brγ, and He I λ10380 all rise relative to Hγ during the decay phase of the flare. The best-fitting models in our suite of atmospheres indicate that an increase in Ca II K is always coupled with a decrease of the Paschen and Brackett lines. The time evolution of flares may involve different atmospheric components covering the surface of the star with changing filling factors (e.g., Kowalski et al. 2010). It is possible that a linear combination of two or three different one-dimensional atmospheres with changing filling factors would reproduce the time evolution of this flare.

6. SUMMARY

During nearly 50 hr of simultaneous photometric and spectroscopic observations on four active M dwarfs, we saw 16 total flares, 3 of them with accompanying infrared emission lines. The strongest flare (∆μ = 4.02) occurred on EV Lac on UT 2009 October 27. It showed emission from Hγ, Hδ, He I λ4471, Ca II K, Pβ, Pγ, Pδ, Brγ, and He I λ10830. A weaker flare (∆μ = 1.68) on EV Lac on UT 2010 November 27 showed only emission from Pβ, Pγ, and He I λ10830. Remarkably, the
He\textsc{i} $\lambda$10830 emission was twice as strong compared to P\textsc{b} and P\textsc{y} as it was in the $\Delta U = 4.02$ flare. The weakest flare with infrared emission ($\Delta U = 1.38$) occurred on YZ CMi on UT 2011 February 14; P\textsc{b}, P\textsc{y}, and He\textsc{i} $\lambda$10830 were just above their detection limits. We estimate a duty cycle of 2.8\%–4.6\% for observing the strongest infrared emission line (P\textsc{b}) during flares on active mid-M dwarfs. These observations confirm that flares are detectable in the infrared portion of M dwarf spectra, which is much brighter in quiescence than the bluer portions of M dwarf spectra which are typically used to detect flares.

Using a hotter chromosphere than previous one-dimensional static flare models (e.g., Christian et al. 2003; Fuhrmeister et al. 2010), the ratios of Ca\textsc{ii} K, He\textsc{i} $\lambda$4471, H\textsc{a}, the Paschen lines, and Br\textsc{y} to H\textsc{y} can be relatively well reproduced. The generation of Ca\textsc{ii} K in the hot, upper portion of the atmosphere is distinct from previous results and is necessary to produce more Ca\textsc{ii} K than Paschen series emission, which is observed during our strongest flare. This result confirms that infrared emission is a useful constraint on the atmospheric heating during M dwarf atmospheres.

The strength of emission from He\textsc{i} $\lambda$10830 is not predicted from our one-dimensional model, but including a detailed treatment of backwarming from the corona (e.g., Allred et al. 2006) may be warranted, based on solar results. Modeling He\textsc{i} $\lambda$10830 is also complicated by its different emission strengths compared to P\textsc{b} and P\textsc{y} in the two flares on EV Lac, but these differences show that He\textsc{i} $\lambda$10830 has potential to constrain different backwarming scenarios during a variety of flares. The time evolution of the largest flare is not reproduced by our one-dimensional models, but a combination of multiple models with different filling factors (e.g., Walkowicz 2008; Kowalski et al. 2010) or detailed radiative hydrodynamic modeling with non-thermal beam heating (e.g., Allred et al. 2006) may provide a better match to the flare emission.

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