Near-Ultraviolet Spectra of Flares on YZ CMi

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ABSTRACT. Near-ultraviolet spectroscopic data obtained with the Hubble Space Telescope STIS (Space Telescope Imaging Spectrograph) instrument on the dMe flare star YZ Canis Minoris (YZ CMi) were analyzed. Flare and quiet intervals were identified from the broadband near-UV light curve, and the spectrum of each flare was separately extracted. Mg ii and Fe ii line profiles show similar behavior during the flares. Two large flares allowed time-resolved spectra to be analyzed, revealing a very broad component to the Mg ii k line profile in at least one flare spectrum (F9b). If interpreted as a velocity, this component requires chromospheric material to be moving with FWHM ∼ 250 km s⁻¹, implying kinetic energy far in excess of the radiative energy. The Mg ii k line profiles were compared to recent radiative hydrodynamic models of flare atmospheres undergoing electron beam heating. The models successfully predict red enhancements in the line profile, with a typical velocity of a few km s⁻¹, but do not reproduce the flares showing blue enhancements, or the strongly broadened line observed in flare F9b. A more complete calculation of redistribution into the line wings, including the effect of collisions with the electron beam, may resolve the origin of the excess line broadening.

1. INTRODUCTION

Spectroscopic signatures of flares on M dwarfs have been sporadically explored, mostly at optical wavelengths, since the pioneering observations of UV Ceti by Joy & Humason (1949). Principal features observed during flares include strong continuum radiation rising toward the blue and near-ultraviolet; broad, enhanced hydrogen Balmer series emission lines; enhanced emission in high-temperature lines, such as He i, He ii, C iv, N v, and Si iv; enhanced X-ray emission; and bursts of radio emission (e.g., Kunkel 1967; Jackson et al. 1989; Hawley & Pettersen 1991; Eason et al. 1992; Osten et al. 2005).

YZ Canis Minoris (YZ CMi, also known as Gliese 285), an active dM4.5e star with V = 11.1 and d = 6 pc (Perryman et al. 1997), has been a popular target for flare-monitoring campaigns, due to its proximity and strong activity, which improves the chances of observing a flare. Extensive multiwavelength spectroscopic flare studies of YZ CMi include those of Kahler et al. (1982), Worden et al. (1984), and van den Oord et al. (1996).

Previously, no M dwarf flare star has been systematically observed with high-resolution near-UV spectroscopy in the region where the important chromospheric Mg ii h and k lines, and numerous Fe ii emission lines, are produced. The International Ultraviolet Explorer (IUE) did not have the sensitivity to provide much time resolution or spectral resolution during flares, although strong Mg ii emission was observed from the dM3e star AD Leo during the decay phase of an exceptionally large flare (Hawley & Pettersen 1991). Linsky et al. (1982) carried out an early pioneering study of ultraviolet emission in active cool stars with IUE, while a later comparative study of Mg ii h and k emission with X-ray emission was undertaken for a sample of M dwarfs, including YZ CMi, by Mathioudakis & Doyle (1989). Broadband near-UV emission during flares has been recently studied by Mitra-Kraev et al. (2005), using XMM-Newton data, and by Robinson et al. (2005), using GALEX data.

The data presented here were obtained as part of a larger multiwavelength campaign to observe YZ CMi in 2000. We use these near-UV spectra to examine the Mg ii and Fe ii emission-line profiles in YZ CMi during quiescence and flares, and to study the behavior of the Mg ii emission in the flares that are large enough to be subdivided into separate, time-resolved flare spectra. We also compare the observational data for these chromospheric lines with predictions from our new generation of radiative hydrodynamic models (Allred et al. 2005, 2006). The new models incorporate detailed radiative transfer in atmospheres that are heated by nonthermal electrons and are undergoing significant mass motions as heated material flows upward (evaporation) and downward (condensation) within a magnetic loop. The models were designed to predict velocities and line profiles of chromospheric emission lines and are therefore suitable for comparison with the Mg ii observations described here.

2. OBSERVATIONS

The Hubble Space Telescope (HST) observed YZ CMi on 2000 February 5–6 as part of Guest Observer program 8129 (PI: R. Robinson). We reanalyze these archival data as part of

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Archival Research program 10312 (PI: S. Hawley). The Space Telescope Imaging Spectrograph (STIS; Kimble et al. 1998) was used with the medium-resolution near-ultraviolet (NUV) echelle grating (E230M) and the 0.2 arcsec aperture. The E230M spectra have a nearly constant (% 1.5%) dispersion of 4.88 km s\(^{-1}\) pixel\(^{-1}\). The line-spread function (LSF) for the 0.2 × 0.2 arcsec aperture has a FWHM of 1.8–1.9 pixels over the wavelength range 2400–2800 Å, corresponding to a resolving power of \(R = 33,000\). These are the only STIS spectra of an M dwarf flare star at NUV wavelengths that exist in the HST archive. Data were obtained during six consecutive orbits, with exposure times ranging from 32 to 40 minutes, over a 6.5 hr total time span. The MAMA detector time-tag mode was used for the observations, resulting in an event list for each exposure that contains the detection time and location of every photon detected.

To construct light curves of the integrated light obtained during each exposure, we used an extraction window that was 11 pixels wide, centered on each echelle order, to assign all time-tag events to either source or background regions on the MAMA detector. We then divided each exposure into 100 uniform time bins (19–24 s in duration, depending on the individual exposure lengths, which range from 32 to 40 minutes; see Table 1), obtaining separate light curves for the source and background regions. For each exposure, we fitted the background light curve with a sixth-order polynomial, scaled the result by the ratio of source to background pixels, and then subtracted this predicted background from the source light curve to obtain a total observed stellar count rate for each time bin. Errors for each time bin include Poisson noise from the subtracted background.

Figure 1 illustrates the resulting light curves for the six exposures. The flaring and quiet intervals F1–F10 and Q1–Q8 were assigned by qualitative inspection of the light curves and are labeled on the figure. Table 1 provides relevant information about each spectral interval. Column (1) lists the number of the exposure containing the time interval. Exposure number \(N\) maps to HST data set 059k010N0. The second and third columns give the start and end time of each interval, expressed in minutes since the beginning of each exposure. Column (4) gives the label assigned to each time interval, with Q labels indicating quiet intervals and F labels indicating flare intervals. The numbers were assigned sequentially in time for individual intervals. Columns (5) and (6) give the total count rate and standard deviation for each interval. Although the flaring and quiet intervals were assigned qualitatively, it is clear from these data that the flaring intervals have both higher count rates and larger scatter. The exceptions are the late decay phases of the two large flares, labeled F2c and F9c. Since we wanted to investigate the evolution of the emission lines in these late phases, we retain those as flare intervals. Also note that quiet interval Q7 has a relatively high count rate and shows significant low-level variability in the light curve, but no obvious flares. We include it as a quiet interval after ensuring that the Q7 spectrum shows no more than 1.2% variation compared to the summed quiet spectrum over all other intervals. Since Q7 represents almost one-third of the quiet exposure time, including it increases the signal-to-noise ratio (S/N) of the summed quiet spectrum.

We used the IRAF package STSDAS (ver. 3.3.1, 2005 March 31) to split the time-tag event lists into the quiet and flaring time intervals and then to extract spectra for these intervals. To split the event lists, we used the task inttag (ver. 1.1, 2000 January 26). To extract the spectra, we used the task calstis (ver. 2.18, 2005 February 15) with the best calibration reference files available on 2005 July 10. The calibration process removed radial velocity shifts caused by orbital motion of the spacecraft around the Earth and the Earth around the Sun. Hence, every extracted spectrum is in (the same) heliocentric reference frame. Table 2 provides the UT and Julian Date (JD) at the start of each exposure.

YZ CMi has a measured rotation velocity \(v \sin i = 6.5\) km s\(^{-1}\) (Delfosse et al. 1998). With a nominal radius of 0.2 \(R_\odot\), this corresponds to a minimum period of 1.6 days, considerably longer than the total (consecutive) elapsed time of the HST exposures (~0.4 days). The individual exposures comprise <2% of the minimum period, indicating negligible change in the location of a given active region during a single exposure. We do not see strong evidence for smooth (nonflaring) variability within a given orbit, as was found by Robinson et al. (1999) in their NUV photometric observations of YZ CMi using HST with the High Speed Photometer instrument. Our analysis of

### Table 1

| Exposure | \(t_{\text{start}}\) | \(t_{\text{end}}\) | Label | Rate | \(\sigma\text{(Rate)}\) |
|----------|------------------|-----------------|-------|-------|-----------------|
| 1        | 0                | 22              | Q1    | 14.4  | 6.7             |
| 2        | 22               | 30              | F1    | 30.0  | 15.8            |
| 3        | 0                | 5               | F2a   | 62.0  | 70.9            |
| 4        | 5                | 10              | F2b   | 38.7  | 9.7             |
| 5        | 10               | 15              | F2c   | 17.9  | 5.1             |
| 6        | 15               | 40              | Q2    | 7.7   | 5.6             |
| 7        | 0                | 17              | Q3    | 12.2  | 5.0             |
| 8        | 17               | 40              | F3    | 25.7  | 13.4            |
| 9        | 1                | 4.5             | F4    | 30.1  | 31.1            |
| 10       | 4.5              | 15.5            | Q4    | 7.6   | 7.8             |
| 11       | 15.5             | 19              | F5    | 43.3  | 24.2            |
| 12       | 19               | 27.5            | Q5    | 7.0   | 7.7             |
| 13       | 27.5             | 30              | F6    | 34.9  | 6.1             |
| 14       | 30               | 37              | Q6    | 10.2  | 5.9             |
| 15       | 37               | 39              | F7    | 164   | 121             |
| 16       | 0                | 1.5             | F8    | 44.2  | 3.8             |
| 17       | 1.5              | 37              | Q7    | 21.0  | 7.1             |
| 18       | 37               | 39              | F9a   | 55.2  | 34.1            |
| 19       | 8                | 11.5            | F9b   | 37.4  | 17.9            |
| 20       | 11.5             | 17              | F9c   | 8.4   | 4.4             |
| 21       | 17               | 25              | F10   | 26.9  | 7.2             |

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Fig. 1.—Light curves showing the total count rate integrated over the 2300–3050 Å STIS E230M bandpass during each of the six exposures on YZ CMi. See text for details about the construction of the light curves. The flaring (F1–F10) and quiet (Q1–Q8) intervals are indicated.
the STIS spectroscopic data is not presently suitable for comparison with their flare frequency analysis, but it would be interesting to reanalyze the MAMA time-tag data in sum over shorter time intervals to more rigorously identify individual flares. However, this is beyond the scope of the present paper.

2.1. Light Curves and Spectra

Figure 1 and Table 1 show that YZ CMi was in an obvious flaring state for approximately 40% of the total 224 minutes of exposure time comprising the six separate exposures. The flux emitted in the near-UV bandpass sampled here (2300–3050 Å) is approximately $4.2 \times 10^{12}$ ergs s$^{-1}$ cm$^{-2}$ during quiet periods. Using a distance of 6 pc for YZ CMi, the quiescent energy emitted from the visible hemisphere during the 242 minutes of exposure was $\sim 1.2 \times 10^{32}$ ergs, while the energy emitted by flares was $\sim 1 \times 10^{31}$ ergs, giving a total energy in this bandpass of $\sim 1.3 \times 10^{32}$ ergs. The flare energy comprises $\sim 8\%$ of the total.

Figure 2 illustrates the spectrum summed over all quiet intervals. The line identifications were made using the Chianti database (Dere et al. 1997; Landi et al. 2006). Clearly, most of the emission lines in the near-UV come from Fe $\text{\textsc{ii}}$, with the notable addition of the Mg $\text{\textsc{ii}}$ h and k lines and minor contributions from Si $\text{\textsc{ii}}$, S $\text{\textsc{ii}}$, and Al $\text{\textsc{ii}}$.

Figure 3 shows the summed spectrum over all flare intervals, with the quiet spectrum subtracted. Note that subtracting the quiet spectrum without scaling assumes that the area covered by the flare is negligible compared to the area of the visible hemisphere of the star. As discussed in § 3, the flare area required to best match the observed Mg $\text{\textsc{ii}}$ k emission to the model predictions is $\sim 0.5\%$ of the observed surface, which supports the assumption that the flare area coverage is negligible. The flare-only emission shown in Figure 3 is primarily evident in the Mg $\text{\textsc{ii}}$ and Fe $\text{\textsc{ii}}$ lines, which are enhanced by a similar amount ($\sim 10\%$) over the quiet spectrum. Significant broadening in the Mg $\text{\textsc{ii}}$ lines is also apparent in this flare-only spectrum, and is discussed further in § 2.2 below.

Table 3 gives the energy breakdown between lines and continuum for the flare intervals individually and in sum. The first column shows the excess flare line flux calculated from the subtracted spectrum (flare interval–quiet), with the value in parentheses being the ratio of the flare line flux to the total (line+continuum) flux. The second column shows the same calculation for the continuum. Thus, the values in parentheses represent the relative importance of lines and continuum to the excess flare emission, and sum to 1 in each case. As typically seen in stellar flares (e.g., Hawley & Pettersen 1991; Hawley et al. 2003), the larger flares are dominated by the continuum contribution; e.g., F2a, F4, F7, and F9a, where $\sim 70\%$–$90\%$ of the energy is contained in the continuum. Two of the flares (F1 and F3) actually showed negligible line enhancements (formally negative, but within the uncertainties of being small-scale variability) but well-detected continuum enhancements. A large M dwarf flare was recently observed with GALEX using a broad bandpass NUV filter (Robinson et al. 2005) and was analyzed assuming that all of the NUV emission was from the continuum. This appears to be reasonably justified by our analysis of the NUV flare spectra presented here. However, some smaller flares (F5 and F8), and the decay phases of large flares (F2b, F2c, and F9b), emit as much as 50% of their energy in the emission lines. In sum, the flaring intervals show that most flare energy is emitted in the continuum (77% compared to 23% in line emission), while the quiet spectrum is dominated by the emission lines, with 65% of the energy emitted in lines compared to 35% in the continuum.

The NUV emission-line energy is quite evenly divided between Mg $\text{\textsc{ii}}$ and Fe $\text{\textsc{ii}}$ in this bandpass, with the Fe $\text{\textsc{ii}}$/Mg $\text{\textsc{ii}}$ energy ratio being 0.97 in the quiet spectrum, and 1.01 in the flare spectrum. Each Mg $\text{\textsc{ii}}$ line carries much more energy than any individual Fe $\text{\textsc{ii}}$ line, but there are a large number (78) of identified Fe $\text{\textsc{ii}}$ lines in this region, which makes them energetically important in sum. Our results for the quiet ratio are in agreement with those found in Linsky et al. (1982).

2.2. Flares

The Mg $\text{\textsc{ii}}$ lines undergo significant changes in their line profiles during the flaring intervals. Figure 4 shows the Mg $\text{\textsc{ii}}$ k line profiles for the individual flares (F1–F10), obtained from the summed spectra over the extent of each flaring episode.
Fig. 2.—High-S/N quiet spectrum of YZ CMi in the near-UV, produced by coadding all of the quiet intervals from Fig. 1. Emission lines identified in the Chianti database are labeled. The Mg ii h and k lines extend off the figure, with peaks at $2.3 \times 10^{-12}$ and $1.8 \times 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$, respectively.

Flares F2 and F9 were large enough that it was possible to split them up into impulsive, peak, and decay phases, shown as F2a–c and F9a–c in Figure 4. The quiet flare profile is shown for comparison as the dotted line in each panel. It is clear that the quiet flux dominates the total, even during flares, indicating that the flare area coverage is very small and that Mg ii k is
Fig. 3.—Flare spectrum produced by coadding flare intervals from Fig. 1; the quiet spectrum from Fig. 2 was subtracted to produce this flare-only spectrum. The Mg II $h$ and $k$ lines extend off the figure, with peaks at $6.1 \times 10^{-14}$ and $6.4 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$, respectively.
Fig. 4.—Mg ii k line profiles for each of the flare intervals (dotted line: quiet profile; dashed line: flare profile), including the three subdivisions of flares F2 and F9. The data are displayed on a logarithmic flux scale so that enhancements in the line wings during the flares are evident. The quiet profile is included for comparison in each panel.
already a very strong line, even in the quiet chromosphere. This behavior is similar to H$_\alpha$, which also responds only slightly to flares in early–mid M dwarfs (e.g., Hawley et al. 2003), although it responds more strongly in late M dwarfs (cf. Liebert et al. 1999). This is in contrast to lines such as He i and ii and the higher order Balmer lines, which become significantly stronger during flares, often dwarfing the quiet contribution to the line flux (Hawley & Pettersen 1991).

Figure 5 shows the subtracted profiles for each flare (i.e., flare-quiet, as in Fig. 3) in order to examine possible velocity shifts during the flare. The flares are shown on the same vertical scale such that strong flares have significant excess emission,
and small flares have very little. It is clear that some flares (F1, F2, F3, F7, and F10) show a blue wing enhancement and red wing deficit, while others show the opposite behavior (red wing enhancement and blue wing deficit; F4 and F9), and still others show both blue and red enhancements (F5 and F8) or deficits (F6). For simplicity, we use only the Mg ⅱ k line in
the following analysis, as the Mg II h line exhibited very similar behavior in all cases.

The flares are grouped according to the appearance of the excess flare emission in Figure 6 (blue enhancements) and Figure 7 (red enhancements), with the left panels showing Mg II k and the right panels the strong Fe II UV1 line at 2600.2 Å. In general, the enhancements seen in Mg II k are also seen in the Fe II data (albeit at a lower level and with poorer S/N), as expected, since these lines are formed in approximately the same temperature region of the atmosphere. Simple Gaussian fits to the enhancement features give wavelength shifts for each of these flares, as shown in Table 4. The shifts are not large, typically a few km s$^{-1}$/H11002 in both the upward (blueshift) and downward (redshift) directions. The Sun also shows such velocity shifts, even outside of obvious flares. These have been attributed to asymmetric heating in active region loops (Winebarger et al. 2002).

To verify that these apparent velocity shifts are not artifacts of the data reduction, we compared the magnitude and sense of the shift in each flare with the peculiar velocities of HST and the Earth during the time period in the orbit that the flare occurred, and found no correlation. We see no evidence that the observed velocity shifts are instrumental in nature, and therefore presume that they represent real effects in the NUV emission lines emitted by the star. We discuss the velocities compared to those expected from our flare models in § 3 below.

Figure 8 shows the time evolution of the Mg II k emission for the largest flares, F2 and F9. Flare F2 exhibits rather simple behavior, with the narrow central profile strongly enhanced on the blue side in the impulsive phase (F2a), and decreasing monotonically during the flare decay (F2b and F2c). In contrast, flare F9 is quite unusual, initially (F9a) showing a strong red enhancement in the central profile, but then developing very broad, symmetric wings in F9b. On closer inspection of Figure 4, it appears that there is evidence for similarly broad wings in F7 and F9a. These data are reminiscent of those in Doyle & Byrne (1987), where extensive, symmetric line broadening was seen in the hydrogen Balmer lines during a flare on YZ CMi. Broad hydrogen lines during flares are usually interpreted as being due to Stark broadening (Donati-Falchi et al. 1985; Hawley & Pettersen 1991; Johns-Krull et al. 1997; Jevremovic et al. 1998), but Doyle & Byrne were unable to find a satisfactory fit to the data with Stark profiles. Instead they inferred symmetric red- and blueshifted emitting regions, or turbulent motions, of the order of a few hundred km s$^{-1}$. This is typical of the broad component often seen in transition region and coronal emission lines, which is often ascribed to overlapping emission from multiple explosive microflaring events, leading to high-velocity mass motions (Antonucci et al. 1993; Wood

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**TABLE 4**

| Flare | $\lambda_0$ (Å) | $\Delta \lambda$ (Å) | $V$ (km s$^{-1}$) | $\Delta V$ (km s$^{-1}$) |
|-------|----------------|------------------|----------------|------------------|
| F1    | 2803.53        | 0.02             | -4.65          | 2.14             |
| F2a   | 2803.53        | 0.04             | -4.65          | 3.21             |
| F3    | 2803.54        | 0.05             | -3.58          | 5.35             |
| F4    | 2803.70        | 0.03             | 13.52          | 3.21             |
| F7    | 2803.56        | 0.04             | -1.44          | 4.28             |
| F9a   | 2803.70        | 0.04             | 13.52          | 4.28             |
| F10   | 2803.59        | 0.04             | 1.59           | 4.28             |
Fig. 8.—Time evolution of the Mg ii k subtracted (flare—quiet) line profiles, illustrated for intervals F2a–c and F9a–c. Flare F2 shows consistent behavior throughout the impulsive and decay phases, while flare F9 changes from a narrow, red enhanced line in F9a to a symmetric but very broad line in F9b. See text and Fig. 9 for further discussion of the broad line wings in F9b.

et al. 1996, 1997; Vilhu et al. 1998). However, those broad components are not associated with large flares, but appear even in the quiescent spectra of active (earlier type) stars and the Sun. The phenomenon we have observed appears to be directly related to the large flare heating event F9 and does not appear in quiescence or in the other flaring events (except possibly flare F7). In particular, it does not occur in the other large flare we observed, flare F2.

In the present case, we do not expect that Stark broadening will be important for the Mg ii resonance lines. Fleurer et al. (1977) determined experimentally that the Stark broadening of these lines varied with core width between 0.05 and 0.10 Å and wings extending to ~0.1–0.2 Å for temperatures of (1–3) × 10^4 K and an electron density of N_e = 10^{17} cm^-3, much higher than expected in the M dwarf atmosphere. Figure 9 illustrates a simple Gaussian fit to the underlying broad component in F9b, yielding a redshift of 0.5 ± 0.08 Å (53 ± 8 km s^-1) and FWHM of 2.36 ± 0.58 Å (250 ± 60 km s^-1). If interpreted as velocities, the FWHM would suggest turbulent emitting material with typical speeds >100 km s^-1 within a bulk condensation moving downward at roughly 50 km s^-1. Both the bulk and turbulent velocities exceed the sound speed in the chromosphere, which is roughly 10–20 km s^-1. Adopting a chromospheric mass density of 1 × 10^{-10} g cm^-3 during the flare (Allred et al. 2006) and a Mg ii emitting region height of 300 km (see Figs. 10 and 11 below), along with a flare area of 0.5% of the visible stellar surface, the kinetic energy implied by chromospheric material moving at such large velocities far exceeds the energy radiated by the flare, by several orders of magnitude.

Wood et al. (1996) found that the Mg ii h and k lines in HR
1099, an active RS CVn binary system, showed a broad component during quiescence that looked similar to the broad components observed in the $\text{C}\ iv$ transition region resonance lines, with FWHM $\sim 170$ km s$^{-1}$. They were skeptical, as we are, that the dense, optically thick chromosphere could respond to explosive microflaring events to drive mass motions at these velocities, and they carried out detailed modeling that led them to suggest that opacity effects in the line wings might account for the observed broadening. Again, however, these effects were associated with the star in quiescence, not in the midst of an obvious strong flare.

### 3. COMPARISON TO FLARE MODELS

Recently, Allred et al. (2005, 2006) produced models of solar and stellar flares aimed at understanding the chromospheric and transition region emission. The models use solutions to the one-dimensional equations of radiative hydrodynamics, including non-LTE radiative transfer in H, He, and Ca $\ni$, with flare heating provided by an electron beam. The results include predictions of atmospheric structure (temperature, density profiles), velocity, and line profiles at many time steps during an episode of flare heating. We used the results of their preflare and F10 models to investigate the Mg $\ni k$ emission during the YZ CMi flares. The F10 model used here represents an average midflare atmosphere near a time step of $\sim 85$ s; see Allred et al. (2006). Note that the F10 model refers to electron beam heating of $10^{10}$ ergs s$^{-1}$ cm$^{-2}$ during the model flare and is not to be confused with our observed F10 flare presented in § 2 above.

Since the Allred et al. models do not predict Mg $\ni k$ emission-line profiles, the preflare and F10 models were further analyzed with the “RH” non-LTE radiative transfer code described in Uitenbroek (2001). The RH code is based on the Multilevel Accelerated Lambda (MALI) formalism of Rybicki & Hummer (1991, 1992), which allows both bound-bound and bound-free radiative transitions to overlap in wavelength. It also includes the effects of partial redistribution for strong bound-bound transitions, such as Mg $\ni h$ and $k$.

Figure 10 shows the temperature and density (electron, hydrogen) structure of the preflare atmosphere, together with the resulting Mg $\ni k$ line profile and the contribution function. Figure 11 is a similar plot for the model F10 flaring atmosphere. The contribution function indicates the atmospheric height where the observed emission of interest is produced. It is de-
Fig. 11.—Same as Fig. 10, but for the flare F10 model. The flare model clearly shows the effect of beam heating on the chromospheric temperature and density distributions, and the contribution function indicates that the Mg $\text{ii} \lambda$ emitting region is asymmetric due to the velocity fields in the atmosphere. The line profile reflects this asymmetry.

defined as the integrand in the equation for the emergent intensity:

$$I_{\nu}(0) = \frac{1}{\mu} \int_{z} S_{\nu} \chi_{\nu} e^{-\tau_{\nu}/\mu} dz,$$

where $I_{\nu}(0)$ is the emergent intensity at frequency $\nu$, $\mu$ is the cosine of the angle between the vertical and the emergent ray (we show the results for $\mu = 1$; i.e., a ray that emerges vertically), $S_{\nu}$ is the source function, $\chi_{\nu}$ and $\tau_{\nu}$ are the monochromatic opacity and optical depth, respectively, and $z$ is the atmospheric height.

As shown in the figures, the Mg $\text{ii} \lambda$ line is formed in the upper chromosphere over a temperature range from 8000 K (line wings) to 20,000 K (line core). At 20,000 K the density is lower; hence, there is relatively less emitting material. This lower emission in the line core causes the central reversal in the line profile (see Fig. 10). In the flaring atmosphere, there is an outward directed velocity where the core is formed, producing an asymmetric profile (see Fig. 11) with a blueshifted core. The contribution function (Fig. 11, top center) also indicates that the red wing is formed in a lower, denser region than the blue wing. Therefore, more flux is produced in the red wing.

We scaled the model flare line profile by 0.5%, subtracted it from the preflare line profile, and smoothed it to the $R = 33,000$ resolution of the data to produce the Mg $\text{ii} \lambda$ subtracted (flare–quiet) model line profile shown in Figure 12. Note that at this resolution, the prominent central reversals in the model profiles are much reduced, although the models still do not have the smooth appearance of the observed line profiles in Figure 4. Nevertheless, the subtracted flare profile in Figure 12 looks quite similar to the observed profile during the impulsive phase of flare F9 (i.e., F9a; see Fig. 8). The velocity shifts implied by the redshifted emission are $\sim 4 \text{ km s}^{-1}$ in the model profile, and $\sim 13.5 \text{ km s}^{-1}$ in the observed profile.

However, the models do not reproduce the upward-moving Mg $\text{ii} \lambda$ material seen in the observed blue enhancement flares (Fig. 6), nor do they show the very broad component in the decay phase of flare F9 (i.e., F9b; see Fig. 9). In fact, if the broadening is interpreted as being due to emitting material moving with high velocity, the models never produce anything close to the velocities required at the depth of the Mg $\text{ii}$ emitting region.
Alternatively, the very broad wings seen in flare F9 may be due to enhanced redistribution of photons from the optically thick Doppler core to the less thick radiative damping wings, due to some process associated with the flare. A comparison of quiet and flare profiles in Figure 4 suggests that the line core is saturated, even in the quiet atmosphere, so redistribution is likely to be important. The Allred et al. (2006) dynamical simulation includes the effects of the electron beam on atmospheric heating and the statistical equilibrium of H, but not Mg. The RH code that we use to generate spectra from the Allred et al. flare model includes a standard implementation of partial redistribution. A "coherency fraction" (see Uitenbroek 2001, eq. [13]) mixes coherent scattering and complete redistribution in proportion to the depopulation rate (due to radiation and inelastic collisions) and elastic collision rate, respectively. Typically, elastic collisions are due to van der Waals and Stark broadening. However, the RH code does not include the contribution to the elastic collision rate due to interactions with the electron beam.

We speculate that the inclusion of the beam collisions would enhance the collisional rates, increasing the redistribution of line core photons into the wings and possibly producing the far wing line emission seen in the data. We plan to investigate this possibility in our next generation of flare models.

4. SUMMARY

We analyzed six orbits of HST STIS near-UV spectroscopic data on YZ CMi and found that the star was flaring approximately 40% of the time. The flares contributed ~8% of the energy observed in the near-UV (2300–3050 Å) during the 224 total minutes of exposure time. Ten flaring and eight quiet intervals were identified, and two of the flares (F2 and F9) were large enough to divide into subintervals to study the time evolution of the near-UV emission during those flares. The Mg ii k emission line was examined in detail and was found to change significantly between different flares, showing blue enhancements in some flares, red enhancements in others, and symmetric enhancements in the wings or core in still others. This indicates that Mg ii emitting material may experience outward- or inward-directed velocities (i.e., evaporation or condensation), depending on the individual flare heating. The strongest Fe ii line (UV1) showed behavior similar to that of the Mg ii k line. Furthermore, flare F9 showed a remarkable line broadening, which fit a Gaussian profile corresponding to a velocity FWHM of ~250 km s⁻¹. This velocity is highly supersonic, and if the broadening is interpreted as being due to either symmetric mass motions or turbulence, it would imply a kinetic energy during the flare that vastly exceeds the radiated energy (by several orders of magnitude). Overlapping emission due to explosive microflares, as has been suggested to explain the broad components observed in optically thin transition-region emission lines, does not appear to be a physically plausible explanation for the emission from the Mg ii lines, which are formed in a dense, optically thick regime.

The data were compared to Mg ii k line profiles generated using the preflare and F10 flare models of Allred et al. (2006), together with the RH code of Uitenbroek (2001). The model results indicate that the flare line profile has a red enhancement similar to that seen in the observed F9a spectrum, with a velocity of a few km s⁻¹. However, the models do not predict the blue enhancements seen in some of the observed flares, nor does the Mg ii emitting material attain velocities anywhere near those required to match the broad component of the Mg ii k line seen in the F9b spectrum. The next step in the model calculations is to incorporate collisions with the electron beam into the Mg ii k partial redistribution calculation, which may have the effect of increasing the emission in the radiative damping wings of the line and could therefore explain the observed line broadening.

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REFERENCES

Allred, J. C., Hawley, S. L., Abbett, W. P., & Carlsson, M. 2005, ApJ, 630, 573
———. 2006, ApJ, 644, 484
Antonucci, E., Dodero, M. A., Martin, R., Peres, G., Reale, F., & Serio, S. 1993, ApJ, 413, 786
Delfosse, X., Forveille, T., Perrier, C., & Mayor, M. 1998, A&A, 331, 581
Dere, K. P., Landi, E., Mason, H. E., Monsignori Fossi, B. C., & Young, P. R. 1997, AAS, 125, 149
Donati-Falchi, A., Falciani, R., & Smaldone, L. A. 1985, A&A, 152, 165
Doyle, G., & Byrne, P. B. 1987, in Proc. Fifth Cambridge Workshop, Cool Stars, Stellar Systems and the Sun, ed. J. L. Linsky & R. E. Stencel (Berlin: Springer), 173
Eason, E. L. E., Giampapa, M. S., Radick, R. R., Worden, S. P., & Hege, E. K. 1992, AJ, 104, 1161
Fleurier, C., Sahal-Brechot, S., & Chapelle, J. 1977, J. Quant. Spectrosc. Radiat. Transfer, 17, 595
Hawley, S. L., & Pettersen, B. R. 1991, ApJ, 378, 725
Hawley, S. L., et al. 2003, ApJ, 597, 535
Jackson, P. D., Kundu, M. R., & White, S. M. 1989, A&A, 210, 284
Jevremovic, D., Houbenbine, E. R., & Butler, C. J. 1998, in ASP Conf. Ser. 154, Cool Stars, Stellar Systems, and the Sun, ed. R. A. Donahue & J. A. Bookbinder (San Francisco: ASP), 1500
Johns-Krull, C. M., Hawley, S. L., Basri, G., & Valenti, J. A. 1997, ApJS, 112, 221
Joy, A. H., & Humason, M. L. 1949, PASP, 61, 133
Kahler, S., et al. 1982, ApJ, 252, 239
Kimble, R. A., et al. 1998, ApJ, 492, L83
Kunkel, W. 1967, AJ, 72, 810
Landi, E., Del Zanna, G., Young, P. R., Dere, K. P., Mason, H. E., & Landini, M. 2006, ApJS, 162, 261
Liebert, J., Kirkpatrick, J. D., Reid, I. N., & Fisher, M. D. 1999, ApJ, 519, 345
Linsky, J. L., Bornmann, P. L., Carpenter, K. G., Hege, E. K., Wing, R. F., Giampapa, M. S., & Worden, S. P. 1982, ApJ, 260, 670
Mathioudakis, M., & Doyle, J. G. 1989, A&A, 224, 179
Mitra-Kraev, U., et al. 2005, A&A, 431, 679
Osten, R. A., Hawley, S. L., Allred, J. C., Johns-Krull, C. M., & Roark, C. 2005, ApJ, 621, 398
Perryman, M. A. C., et al. 1997, A&A, 323, L49
Robinson, R. D., Carpenter, K. G., & Percival, J. W. 1999, ApJ, 516, 916
Robinson, R. D., et al. 2005, ApJ, 633, 447
Rybicki, G. B., & Hummer, D. G. 1991, A&A, 245, 171
———. 1992, A&A, 262, 209
Uitenbroek, H. 2001, ApJ, 557, 389
van den Oord, G. H. J., et al. 1996, A&A, 310, 908
Vilhu, O., Muhli, P., Huovelin, J., Hakala, P., Rucinski, S. M., & Collier Cameron, A. 1998, AJ, 115, 1610
Winebarger, A. R., Warren, H., van Ballegooijen, A., DeLuca, E. E., & Golub, L. 2002, ApJ, 567, L89
Wood, B. E., Harper, G. M., Linsky, J. L., & Dempsey, R. C. 1996, ApJ, 458, 761
Wood, B. E., Linsky, J. L., & Ayres, T. R. 1997, ApJ, 478, 745
Worden, S. P., Schneeberger, T. J., Giampapa, M. S., Deluca, E. E., & Cram, L. E. 1984, ApJ, 276, 270