A WHITE LIGHT MEGAFLARE ON THE dM4.5e STAR YZ CMi

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ABSTRACT

On UT 2009 January 16, we observed a white light megaf flare on the dM4.5e star YZ CMi as part of a long-term spectroscopic flare-monitoring campaign to constrain the spectral shape of optical flare continuum emission. Simultaneous U-band photometric and 3350–9260 Å spectroscopic observations were obtained during 1.3 hr of the flare decay. The event persisted for more than 7 hr and at flare peak, the U-band flux was almost 6 mag brighter than in the quiescent state. The properties of this flare mark it as one of the most energetic and longest-lasting white light flares ever to be observed on an isolated low-mass star. We present the U-band flare energetics and a flare continuum analysis. For the first time, we show convincingly with spectra that the shape of the blue continuum from 3350 Å to 4800 Å can be represented as a sum of two components: a Balmer continuum as predicted by the Allred et al. radiative hydrodynamic flare models and a T ∼ 10,000 K blackbody emission component as suggested by many previous studies of the broadband colors and spectral distributions of flares. The areal coverage of the Balmer continuum and blackbody emission regions vary during the flare decay, with the Balmer continuum emitting region always being significantly (∼3–16 times) larger. These data will provide critical constraints for understanding the physics underlying the mysterious blue continuum radiation in stellar flares.

Key words: stars: atmospheres -- stars: flare -- stars: late-type

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1. INTRODUCTION

Due to their strong and persistent surface magnetic fields, active M dwarfs can produce frequent flares, sometimes lasting for many hours and reaching luminosities that approach a significant fraction of the star’s bolometric luminosity (Kunkel 1969; Moffett 1974; Bond 1976; Hawley & Pettersen 1991; Favata et al. 2000; Robinson et al. 2005; Osten et al. 2007; Kowalski et al. 2009). During both solar and stellar flares, emission is seen as line and continuum radiation from X-ray to radio wavelengths, with a prominent mode of radiative energy release occurring in the blue and the near-ultraviolet (NUV) continuum, which is commonly referred to as the white light continuum. Unfortunately, the spectral components which comprise the white light continuum are not well constrained, and therefore the physics of the underlying flare mechanism that gives rise to such a conspicuous signature remains a mystery.

Significant effort has gone into characterizing the white light continuum in stellar flares, beginning with a single-component (hydrogen recombination) model (Kunkel 1969, 1970). A two-component spectral model consisting of hydrogen recombination and an impulsively heated photosphere was first proposed by Kunkel (1970) as a possible explanation of the spread in the broadband flare colors. Time-resolved multi-channel photometry (Mochnacki & Zirin 1980) and spectrometry (Kahler et al. 1982) were obtained longward of 4200 Å for flares on YZ CMi and UV Ceti; at peak, these flare spectra were fit with a Planck function of T = 7400–9500 K, thereby showing evidence of a hot optically thick component present during the impulsive phases of flares. Instrumental effects shortward of the Balmer jump (3646 Å) prevented a precise characterization of the Balmer continuum in the data of Mochnacki & Zirin (1980).

Higher resolution spectra in the blue/NUV were obtained during large flares on AD Leo (3560–4440 Å; Hawley & Pettersen 1991) and CN Leo (3050–3860 Å; Fuhrmeister et al. 2008) showing a nearly continuous rise into the NUV with a T ∼ 8400–11,300 K blackbody; surprisingly, no discontinuity at the Balmer jump was seen in either of these events (see also Eason et al. 1992; García-Alvarez et al. 2002). The white light continuum has therefore been attributed to a single dominant blackbody component with T ∼ 9000–10,000 K (e.g., Hawley et al. 2003). In contrast, flare models predict spectra that are dominated by hydrogen bound-free continua, which provide a poor match to the observations (Hawley & Fisher 1992; Allred et al. 2006, hereafter A06).

A multi-component model was reintroduced by Zhilyaev et al. (2007), who used high-cadence UBVRI photometric observations of the dM3.5e star EV Lac to suggest that the white light emission consists primarily of blackbody radiation at flare peak and hydrogen continuum during the flare decay. However, significant ambiguity results when using broadband photometry to characterize the white light continuum. A06 showed that a flare model spectrum that included a large Balmer jump, when convolved with broadband UV+UBVR filters, actually resembles the shape of a T ∼ 9000 K blackbody. To unambiguously identify the spectral components present during stellar flares, we have therefore begun to compile a large catalog of time-resolved optical/NUV flare spectra on several nearby flare stars. In this Letter, we present time-resolved spectra obtained during a large flare on the dM4.5e star YZ CMi and use results from the recent radiative hydrodynamic (RHD) flare models of A06 to show that both Balmer continuum and hot blackbody components are present in the white light continuum emission. An extensive paper describing our flare catalog, including discussion of the flare emission lines and comparison with models, will be forthcoming.

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2. OBSERVATIONS

2.1. NMSU 1 m Photometry

Photometric observations were obtained in the Johnson U band on UT 2009 January 16 with the New Mexico State University 1 m Telescope at the Apache Point Observatory (APO). The 1 m is operated robotically and is open for observations when the ARC 3.5 m Telescope, located at the same site, is open (Holtzman et al. 2010). The dM4.5e star YZ CMi was observed for nearly 8 hr with an exposure time of 10 s; with readout, the photometric cadence ranged between 20 and 27 s. We performed differential photometry on YZ CMi using the comparison star HD 62525. The night was clear and photometric based on the data from nearby comparison stars. The U-band light curve of YZ CMi is shown in Figure 1(a).

2.2. APO 3.5 m Spectroscopy

We obtained NUV/optical spectroscopy for 1.3 hr during the decay phase of the flare, denoted by vertical lines in Figure 1(a), using the Dual Imaging Spectrograph (DIS) with the ARC 3.5 m Telescope at APO. We used the B400+R300 gratings, providing wavelength coverage from 3350 Å to 9260 Å. The observations were taken through a 1/5 slit which yielded resolutions of $R \sim 625$ (at 4000 Å) and $R \sim 980$ (at 6563 Å), determined from the FWHM of the arc lamp lines. The slit was oriented at the parallactic angle in order to compensate for atmospheric differential refraction (see Filippenko 1982). We observed YZ CMi with exposure times of 10 s, and with readout the total cadence was $\sim 28$ s. In total, 163 flare spectra were obtained simultaneously in both the blue and red bandpasses. The data were reduced using standard IRAF procedures, wavelength calibrated using HeNeArHg lamp spectra, and flux-calibrated by comparing observations of the spectrophotometric standard star Feige 34 to the accepted fluxes of Oke (1990). To correct for variable gray slit loss (e.g., due to guiding errors), we also scaled each spectrum during the flare using the U-band light curve. A spectrum of YZ CMi in its quiescent (non-flaring) state was obtained with the same instrumental setting on UT 2008 November 24 and was used for comparison (see Section 2.2).

3. ANALYSIS

3.1. U-band Flare Energetics

This flare event is remarkable in its total energy, peak luminosity, total duration, and emission morphology. A small precursor, sometimes seen prior to large flares (Moffett 1974), began at 04:14:54 UTC which increased the U-band flux by a factor of $\sim 2$ and represents the onset of the flare event. At 04:32:00 UTC, there was a $\sim 10$ minute impulsive rise to flare peak, where the U-band flux was a factor of $\sim 200$ times the quiescent value. The decay phase included many smaller events, and the U-band flux was still elevated by over a magnitude above quiescence at the end of the night. In Section 4, we discuss the extremely long duration of this event.

The total U-band flare energy is used to quantify the energy release in continuum radiation during stellar flares (Moffett 1974). We integrate under the light curve to obtain an equivalent duration (Gershberg 1972) of $4.25 \times 10^5$ s, which is the amount of time that the star would spend emitting at the pre-flare level to produce the same total amount of energy as the flare. Multiplying the equivalent duration by the non-flaring U-band luminosity of $4.00 \times 10^{28}$ ergs s$^{-1}$ (Moffett 1974) gives $E_{U,\text{flare}} > 1.7 \times 10^{34}$ ergs (this is a lower limit since flare emission is still seen at the time the light curve ends). At peak, the flare was emitting with a U-band luminosity of $8.3 \times 10^{30}$ ergs s$^{-1}$, or $\sim 37\%$ the stellar bolometric luminosity ($L_{\text{bol}} = 10.25$; Reid & Hawley 2005). This flare was $\sim 100$ times more energetic and persisted for more than 10 times as long as the largest U-band flare event observed on this star during 55 hr of monitoring from the large statistical flare study of Moffett (1974) and Lacy et al. (1976). Although it is unknown if the power law fit to the flare-frequency distribution of Lacy et al. (1976) holds at high flare energies, an extrapolation predicts that flares with U-band energies $> 1.7 \times 10^{34}$ ergs occur at a rate of approximately once per month.

3.2. The Flare Continuum

The spectral data were obtained while the U-band emission was still elevated 15–37 times (3–4 mag) over quiescence. Complex morphology is seen in the U-band light curve during this time period (see Figure 1(a)), allowing us to study the flare continuum variations during several smaller impulsive events. Figure 1(b) shows a spectrum ($t = 76.6$ minutes after the flare start) from 3350 Å to 5500 Å near the beginning of our spectroscopic observations during the U-band decay from a large secondary emission peak. A quiescent spectrum of YZ CMi (see Section 2.2) is also shown in Figure 1(b) and has been subtracted from the flare spectrum to give a “flare-only” spectrum. Our spectra have the highest time resolution with high signal-to-noise ratio ($S/N$) in the blue/NUV ($S/N > 50$ at 3600 Å) ever obtained during a large stellar flare. They are also unique in having simultaneous high-quality photometric information so that we may relate the spectral evolution to the light curve morphology.

We have for the first time convincingly identified two distinct continuum components that simultaneously contribute to the optical/NUV flux in flare spectra. The first component dominates the spectrum from 4000 to 4800 Å and exhibits the rising trend of a $T \sim 10,000$ K blackbody, which is plotted on the spectrum in Figure 1(b) using a filling factor, $X_{BB}$, of 0.22% of the projected stellar disk area. We follow Hawley et al. (2003) to constrain the filling factor of blackbody emission as a function of time using the equation

$$F_{flux}(t) = X_{BB}(t) \frac{R^2}{d^2} \pi B_\nu(T_{BB}),$$

where $F_{flux}$ is the flare flux observed at Earth in the continuum windows of 3995–4020 Å, 4140–4210 Å, 4425–4450 Å, and 4600–4800 Å; $R_* = 0.3 \times R_{\text{Sun}}$, $d = 5.97$ pc (Reid & Hawley 2005), and $T_{BB} = 10,000$ K.

From Figure 1(b), it is clear that the blackbody fit does not explain all of the continuum emission at wavelengths shorter than $\sim 3800$ Å. Starting near H10 (3799 Å), there is a rise to H15+H16, the last two apparent Balmer lines in emission. Blueward of $\sim 3700$ Å, the flare spectrum becomes flat into the NUV, and there is excess flux visible above the 10,000 K blackbody at these wavelengths.

A06 presented RHD flare simulations for a medium (F10) and a strong (F11) impulsive flux of nonthermal electrons into...
an M dwarf atmosphere. The A06 models predict strong Balmer continuum radiation with a noticeable Balmer jump at 3646 Å, together with a photosphere that is warmed by $\sim 1200$ K to a temperature of 4600 K. We isolated the Balmer continuum component of the A06 F11 model spectrum taken at the last time step of their simulation ($t = 15.9$ s) and fit it to the observed flare spectra. Figure 1(c) shows the flare spectrum from Figure 1(b) with the 10,000 K blackbody component subtracted and the model Balmer continuum component scaled to the excess emission in the 3600 Å $< \lambda < 3646$ Å region. The shape of the observed excess emission is well described by the F11 flare model prediction (shown in red). Although there is no abrupt discontinuity indicative of a Balmer jump in our observed spectrum, we posit that blending (possibly due to Stark broadening; Donati-Falchi et al. 1985) of the higher order Balmer lines in the 3646 Å $< \lambda < 3800$ Å region effectively hides the sharp discontinuity that is seen in the model spectrum.

3.3. Relative Filling Factors

The filling factor for the F11 model spectrum is calculated by scaling the model flux in the 3600–3646 Å region ($F_\lambda,\text{Model} = 1.14 \times 10^7$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$) to the flux excess observed at Earth after subtracting the 10,000 K blackbody. The contribution function for the Balmer continuum in the F11 model shows that the emission arises from a relatively thin layer in the atmosphere (J. Allred 2010, private communication); it is therefore reasonable to approximate changes in the filling factor to changes in the emitting area of the Balmer continuum.

In the upper panel of Figure 1(d) (black points), we show the ratio of the filling factors for a 10,000 K blackbody and the model Balmer continuum component. The error bars are obtained by using 9000 and 11,000 K temperatures for the blackbody. The ratio for the sample spectrum in Figure 1(b) is $X_{BB}/X_{\text{Model}} = 0.10^{+0.04}_{-0.02}$. The filling factor ratio indicates that the two emission components exhibit significantly different time evolution, with the blackbody source emitting from a region $\sim 3$–16 times smaller than the source of the Balmer continuum. The inferred area filling factor ($X_{BB}$) of the blackbody component is shown separately (red points) and exhibits very similar morphology to the $U$-band light curve (reproduced in the lower panel). Although we expect the total continuum flux to follow the $U$ band since we scaled the spectra to achieve
absolute flux calibration (Section 3.2), it is surprising that only the blackbody component follows the $U$ band.\(^6\) It appears that the deviations from the general flare decay seen in the $U$ band primarily arise from the changing area of the blackbody emission region. When the deviations are strongest near the peaks at $t \sim 95$ minutes and $t \sim 130$ minutes, the spectra are increasingly dominated by the blackbody component. This is consistent with the flare-peak spectra from Kahler et al. (1982), Hawley & Pettersen (1991), and Fuhrmeister et al. (2008), and the photometry of Zhitkova et al. (2007). We also note preliminary evidence of an apparent increase in the best-fit blackbody temperature to $T \sim 13,000$ K at the peak near $t \sim 130$ minutes.

The derived filling factor ratios should be regarded as illustrative since our Balmer continuum spectrum from the F11 model of A06 assumes that the nonthermal electron flux is constant at $10^{11}$ ergs cm$^{-2}$ s$^{-1}$. Also, we use the model flare spectrum from only one time step in the RHD simulation. It is likely that the nonthermal electron flux varied both with time and over the geometry of the flaring region. Any further assessment is beyond the scope of this Letter, but we note that the less energetic A06 F10 flare spectrum at $t = 230.0$ s gives nearly 10 times larger filling factors for the Balmer continuum.

### 3.4. Balmer Line and Continuum Radiation

The time evolution of the Balmer continuum closely follows the hydrogen Balmer lines. We show the variation in the Balmer continuum (using the integrated flux in a 30 Å window centered at 3615 Å) compared to the H$\gamma$ line flux and the $U$ band in the lower panel of Figure 1(d). The fluxes are normalized to the last spectral observation we obtained. The Balmer continuum shows a slow decay throughout our observations, as is typical of the Balmer line radiation (Hawley & Pettersen 1991). This overall decay is probably extended emission from the previous, much more luminous, impulsive events seen in the $U$-band light curve. The larger variations in the Balmer continuum compared to the H$\gamma$ emission may be partially due to small errors in isolating the Balmer continuum by subtracting the underlying blackbody continuum (the H$\gamma$ flux is well measured as it has a local continuum). As noted above in the filling factor discussion and evident by comparing the upper and lower panels of Figure 1(d), the Balmer line and continuum radiation exhibit quite different time evolution compared to the blackbody emission component.

We propose two possible explanations.

1. The hydrogen-emitting regions exhibit a delayed and more gradual response to each successive impulsive (blackbody) event. In this scenario, the gradual increases in hydrogen Balmer emission around $t = 122$ minutes and $t = 137$ minutes are associated with the impulsive events in blackbody emission (upper panel) at $t = 117$ minutes and $t = 127$ minutes, respectively. Also, Balmer emission around $t = 80$ minutes and $t = 105$ minutes is elevated yet only slowly decreasing, and could be gradually declining emission from the large $U$-band peaks at $t \sim 60$ minutes and $t \sim 95$ minutes, respectively.

2. The time evolution of the blackbody emission and the Balmer emission may be anti-correlated. If true, this may provide an important constraint on the origin of the blackbody emission. The possible anti-correlation is most apparent during the $U$-band rise starting at $t = 124$ minutes.

In $\sim 5$ minutes, the Balmer continuum decreases by $\sim 40\%$ while the blackbody filling factor almost doubles. Hydrogen continuum dimming is predicted by flare models (Abbett & Hawley 1999; Allred et al. 2005), but only for very short durations (0.1 s) at the onset of a flare.

More detailed models will be required to understand these complex variations, and in particular, the seemingly anti-correlated trends between the blackbody and Balmer continuum and lines during the time intervals when the blackbody filling factor is increasing in Figure 1(d).

### 4. SUMMARY AND SPECULATION

We observed a white light megaflare on the dM4.5e star YZ CMi in the $U$ band and with simultaneous optical/NUV spectroscopy. The $U$-band energetics and light curve morphology qualify this flare as an extraordinary and rare event, similar to the $\sim 6.6 \times 10^{34}$ ergs flare on YZ CMi seen by Andrews et al. (1969), Lovell (1969), and Kunkel (1969). Following a solar analogy, we speculate that the flaring region on YZ CMi was a complex arcade of sequentially reconnecting magnetic loops. Each reconnecting loop accelerated a beam of nonthermal electrons that impacted the lower atmosphere, producing the observed blue/NUV line and continuum emission. The sum of a large number of individual emitting regions may have enabled this flare to persist for such an unusually long time.

Using high time resolution, high signal-to-noise spectra, we have shown that the blue/NUV flare continuum radiation can be explained as a sum of a $T \sim 10,000$ K blackbody component and a Balmer continuum component, with only the blackbody emission present from 4000 to 4800 Å. The relative filling factors of the two components indicate that the Balmer continuum comes from a larger region, plausibly originating from the flaring loops at chromospheric heights, where the Balmer lines originate. This is consistent with the height of the Balmer continuum emission derived from solar flare data (Hudson et al. 2010), and also with the height of formation predicted by the RHD model of A06.

We found that the blackbody emission arises from a region $\sim 3–16$ times smaller in area than the Balmer continuum emission region. This blackbody emission may possibly originate in concentrated magnetic footpoint regions in the lower atmosphere, similar to the localized areas that emit in white light during solar flares (Metcalf et al. 2003; Fletcher et al. 2007; Isobe et al. 2007; Jess et al. 2008), which are often spatially and temporally coincident with impulsive heating by nonthermal electrons inferred from hard X-ray observations (e.g., Rust & Hegewiz 1975; Hudson et al. 1992; Neidig & Kane 1993; Fletcher et al. 2007). In accordance with this scenario, a large complex of photospheric hot spots may have been created during the first impulsive events in the YZ CMi $U$-band light curve. As the nonthermal electron beams weakened (in energy and/or in spatial extent) so did the areal coverage of these hot spots. This gradual decay extends into the time covered by our spectral observations and is seen in the overall decline of the blackbody areal coverage in the upper panel of Figure 1(d). During our spectral observations, a few new hot spots may have been created at the footpoints of newly reconnected loops, causing the transient increases seen in the $U$ band and in the effective area of the blackbody-emitting region.

We see strong evidence through all of our observations for a blackbody continuum emission component with an approximate temperature of 10,000 K. The persistence of the hot blackbody...
emission indicates that a continual source of particle acceleration and plasma heating likely still exists during the decay phase of the flare. Yet, the A06 models, which employ a nonthermal electron beam as is seen on the Sun, predict the photosphere of an M dwarf to be heated by at most \( \sim 1200 \) K during a large flare. The physical mechanism which generates the strong blackbody emission (presumably from a more strongly heated photosphere) therefore remains unknown. The possible anti-correlation between the Balmer continuum and blackbody emission components may provide an important clue to the nature of the heating mechanism that is responsible for the blackbody emission.

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