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An A star on an M star during a flare within a flare

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Abstract. M dwarfs produce explosive flare emission in the near-UV and optical continuum, and the mechanism responsible for this phenomenon is not well-understood. We present a near-UV/optical flare spectrum from the rise phase of a secondary flare, which occurred during the decay of a much larger flare. The newly formed flare emission resembles the spectrum of an early-type star, with the Balmer lines and continuum in *absorption*. We model this observation phenomonologically as a temperature bump (hot spot) near the photosphere of the M dwarf. The amount of heating implied by our model ($\Delta T_{phot} \sim 16,000$ K) is far more than predicted by chromospheric backwarming in current 1D RHD flare models ($\Delta T_{phot} \sim 1200$ K).

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1. Introduction

Flares on M dwarfs are notorious for producing dramatic outbursts in the near-UV and optical (white light) continuum. The white light continuum has been observed in both the impulsive and decay phases of stellar flares, and the broadband shape of this emission resembles that of a hot blackbody with $T \sim 8500 - 10,000$ K (Hawley & Fisher 1992, Hawley et al. 2003). In contrast, radiative hydrodynamic (RHD) flare models predict a white light continuum with a prominent Balmer continuum in emission (Allred et al. 2006). However, when convolved with broadband filters the model spectrum *also* exhibits the shape of a hot blackbody (Allred et al. 2006). Spectra have been obtained during M dwarf flares (Hawley & Pettersen 1991, Eason et al. 1992, Garcia-Alvarez et al. 2002, Fuhrmeister et al. 2008), showing a clear rise into the near-UV without an abrupt discontinuity at the Balmer jump wavelength ($\lambda = 3646$ Å) or a prominent Balmer continuum in emission. To unravel this complexity in the white light continuum, we have begun a detailed investigation at wavelengths near the Balmer jump using new, time-resolved flare spectra and models.

On UT 2009 January 16, we observed an incredible flare on the dM4.5e star YZ CMi, obtaining high-cadence near-UV/optical (3350−9260 Å) spectra and simultaneous U-band photometry from the ARC 3.5-m and NMSU 1-m telescopes at APO (see Kowalski et al. 2010; hereafter K10). The spectra cover the section of the flare decay shown in Figure 1(a), which consists of several secondary flare peaks. The K10 analysis revealed two continuum components in the flare spectra: a Balmer continuum in emission as predicted by the RHD models and a hot (T∼10,000 K), compact blackbody as seen in previous flare observations.

2. The Secondary Flare Spectra

During the secondary flares, K10 found that the time evolution of the Balmer continuum and Balmer line fluxes are anti-correlated with the areal coverage of the $T \sim 10,000$ K blackbody component. For example, a secondary flare rise begins at $t \sim 124$ min and lasts ∼5 min, resulting in an apparent decrease by 40% in the Balmer continuum flux and an increase by a factor of nearly 2 in the area of the blackbody-emitting region.

The total flare spectra at two times are shown in the inset in Figure 1(a). The times

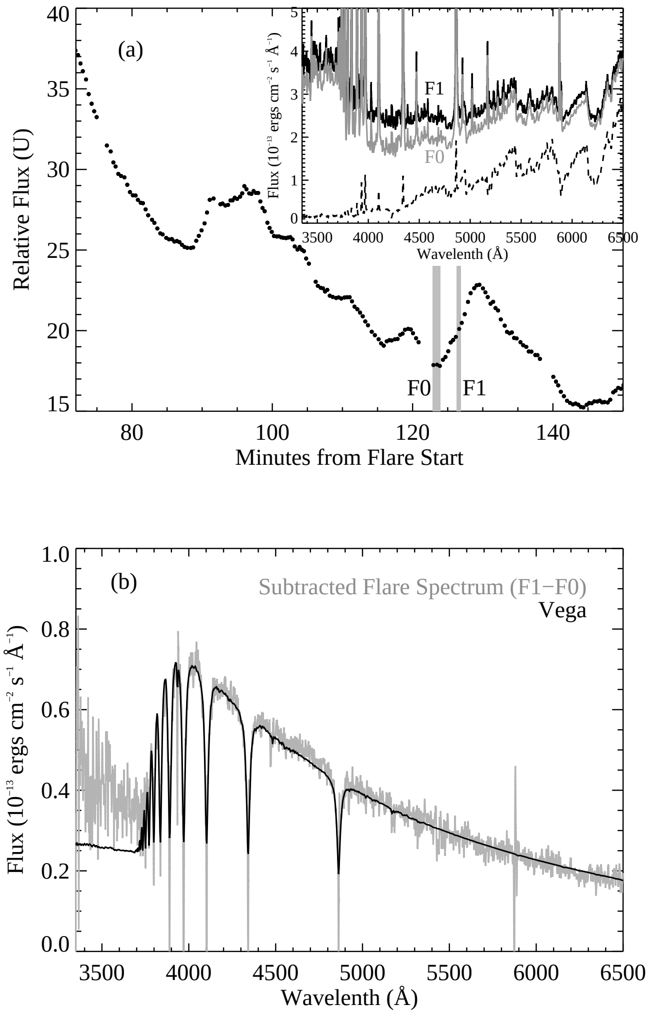

Figure 1. (a) The U-band photometry is shown for the time during which spectra were obtained (see K10 for the complete light curve of the flare). The inset displays averaged spectra immediately before a secondary flare (grey, F0), 2.2 min into the rise phase (black, F1), and during quiescence (dashed line). The times encompassed by each of the flare spectra are denoted by vertical grey bars in the U-band light curve. (b) Subtracting the F0 spectrum from the F1 spectrum isolates newly formed flare emission (grey) during the secondary flare rise. The resulting subtracted flare spectrum resembles the A star Vega with the Balmer features in absorption.

correspond to immediately before the secondary flare rise (F0; $t = 123.4$ min) and 2.2 min into the secondary flare rise (F1; $t = 126.5$ min). The spectra are clearly very complex, consisting of line and continuum emission from both previously heated and newly formed flare regions, in addition to molecular band absorption from the surrounding non-flaring photosphere. We isolate the newly formed flare emission by subtracting the F0 spectrum from the F1 spectrum. The striking features of this subtracted flare spectrum (Figure 1b) include a Balmer continuum and lines in absorption†, in contrast to the total flare spectrum in which the Balmer continuum is in emission. Using continuum windows from 4000−6500 Å, the spectrum is fit by a blackbody with $T \sim$ 16,500 K. We show the spectrum of the A0 V star Vega (from Bohlin 2007) in Figure 1(b) to highlight the remarkably similar characteristics with the spectrum of an early-type star.

3. Phenomonological Modelling with RH

We model the flare spectrum by placing a hot spot, represented by a Gaussian temperature bump with peak temperature of 20,000 K, deep ($\log_{10}$ col mass = 0.5 g cm^{-2}) in the quiescent M dwarf atmosphere (Figure 2a). The emergent radiation is calculated with the static NLTE code RH (Uitenbroek 2001) with a 5 level (plus continuum) Hydrogen atom. We initially iterate to solve for the NLTE background opacities for Hydrogen, and we also consider some relevant molecular species that include Hydrogen (e.g., H_2). The emergent hot spot spectrum is shown in Figure 2(b). The model spectrum has a blackbody temperature of ∼18,000 K, and the Balmer continuum and lines are in absorption, similar to the subtracted flare spectrum. In future work, we will include Helium and metallic transitions, additional levels in the Hydrogen atom, and refined electron densities. We will also further constrain the parameters and time evolution of the hot spot.

4. Summary & Discussion

We find that newly formed emission during a secondary flare resembles the spectrum of an early-type star, such as Vega. Modelling the spectrum phenomonologically‡ by placing a hot spot near the quiescent M dwarf photosphere adequately reproduces the observed spectral shape and Hydrogen absorption features. In a future work, we will show how combining all flare continuum components reproduces the *total* flare spectrum, thereby providing an explanation for the anti-correlation in the time evolution between the Hydrogen emission and blackbody components.

Current, self-consistent 1D RHD models of stellar flares predict that the photosphere is heated by only ∼1200 K, predominantly due to backwarming from the flare chromosphere (Allred et al. 2006). Heating of deep layers by the amount needed to produce a $T_{max} \sim 20,000$ K hot spot is clearly not achieved by a solar-type non-thermal electron beam as energetic as 10^{11} ergs cm^{-2} s^{-1}. More spectral observations of flares with time resolution much less than the rise time, and with spectral coverage farther into the near-UV, are needed to characterize the ubiquity of the phenomena presented in this work.

5. Acknowledgements

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† We use the term *absorption* throughout to refer to 'less emission than the neighboring spectral regions'.

‡ We note that our phenomonological flare models are very similar to the semi-empirical models for the absorption profiles seen during during Ellerman Bombs on the Sun (e.g., Fang et al. 2006).

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Discussion

Kosovichev: 1) Have you been able to observe Doppler shifts? 2) Some theoretical models suggested that condensations behind the downward propagating shock may be responsible for white light emission. What is the satus of these models? Can this be ruled out by the new observations?

Kowalski: First, our spectra have a low spectral resolution, with R∼1000. We aren't concerned about getting very accurate wavelength calibration because we don't want to go off the slit very often to get an arc exposure, in case there is a flare. Flare rise times are very fast, typically 20-40s, so we don't want to miss it. We are more concerned with getting the flare and accurate flux calibration than with the wavlength calibration.

These RADYN models predict a downward condensation wave with speeds of tens of km per second, but this doesn't reach the photosphere with sufficient energy. Most of the energy that reaches the photosphere is backwarming radiation from the Balmer continuum. I'd just like to add that X-ray backwarming was also once thought to be a candidate for the heating in deep layers; however, according to these models only ∼1% of the heating is caused by X-ray backwarming.

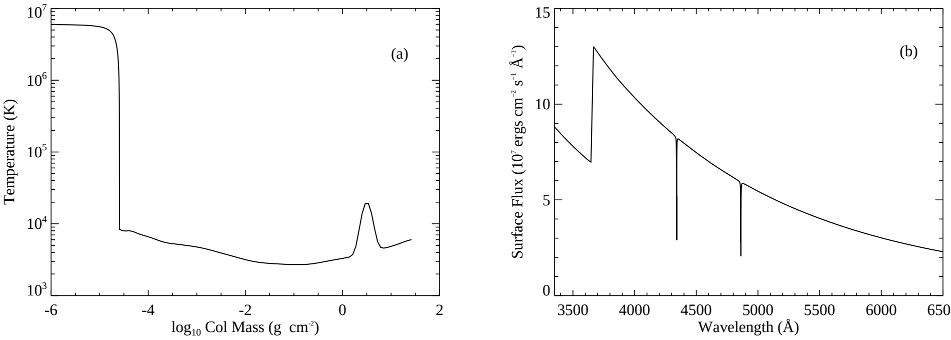

Figure 2. (a) The quiescent M dwarf atmosphere from Allred et al. (2006) with a phenomonological hot spot below the temperature minimum region. (b) The static code RH is used to calculate the emergent flux spectrum for a 6-level Hydrogen atom. The slope of this continuum closely resembles the continuum of the subtracted flare spectrum. Moreover, the temperature bump generates absorption features from Hydrogen.