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State-of-the-Art Observations and Modeling of Stellar Flares

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Flares are observed on a wide variety of stellar types, ranging from closely orbiting binary systems consisting of an evolved member (RS CVn's) and young, nearby super-active M dwarfs (dMe's). The timescales and energies of flares span many orders of magnitude and typically far exceed the scales of even the largest solar flares observed. In particular, the active M dwarfs produce an energetic signature in the near-UV and optical continuum, which is often referred to as the white-light continuum. White-light emission has been studied in Johnson $UBVR$ filters during a few large-amplitude flares, and the best emission mechanism that fits the broadband color distribution is a $T \sim 10^4$ K blackbody (Hawley & Fisher 1992). Time-resolved blue spectra have revealed a consistent picture, with little or no Balmer jump and a smoothly rising continuum toward the near-UV (Hawley & Pettersen 1991). However, the most recent self-consistent radiative-hydrodynamic (RHD) models, which use a solar-type flare heating function from accelerated, nonthermal electrons, do not reproduce this emission spectrum. Instead, these models predict that the white-light is dominated by Balmer continuum emission from Hydrogen recombination in the chromosphere (Allred *et al.* 2006). Moreover, Allred *et al.* (2006) showed that the Johnson colors of the model prediction exhibit a broadband distribution similar to a blackbody with $T \sim 9000$ K.

To critically test these models, and to break the degeneracy using broadband colors for constraining white-light emission processes, we obtained time-resolved blue optical spectra ($\lambda = 3400 - 9200$Å) during a large sample of flares using the ARC 3.5-m telescope at the Apache Point Observatory (APO). We also obtained simultaneous broadband (typically, U band) photometry using the NMSU 1-m and ARCSAT 0.5-m at APO. We analyzed the line and continuum properties during eighteen flares, and we supplemented the sample with two flares that have been previously analyzed using data from other telescopes (Hawley & Pettersen 1991; Schmidt *et al.* 2012). The largest flare in our sample was a $\Delta U = -5.8$ mag (at peak) flare on the dM4.5e star, YZ CMi (Kowalski *et al.* 2010). The spectral monitoring started about an hour after the peak of the flare, when the U band was still elevated at ~ 25 times the quiescent level. The continuum analysis revealed *three* primary continuum components, which varied in relative strength during the flare decay. The energetically dominant component was found to be a moderately hot blackbody component with $T \sim$8500 K, like that observed in previous studies using broadband colors. However, we also found evidence for a Balmer continuum emission component that matched the shape of the RHD model prediction from Allred *et al.* (2006) for a heating flux of 10^{11} erg s^{-1} cm^{-2}. The third continuum component accounts for the gradual phase, excess emission above the extrapolation of the $T = 8500$ K blackbody component to redder wavelengths (e.g., at $\lambda = 6000$Å).

We applied our continuum analysis to the entire flare sample, which consisted of flares covering 2.5 orders of magnitude in peak flux. In particular, we found that the Balmer

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continuum emission is ubiquitous at peak times but is much more dominant in the flares with longer impulsive phase timescales in the U-band light curves. The hot, blackbody emission component exhibits a range of peak temperatures, from $T \sim 9000 - 15\,000$ K; moreover, we discovered absorption features in the Balmer lines and continuum. These absorption features provide additional clues for the origin of the hot, blackbody emission component.

To attempt to reproduce the observed properties of the white-light emission, we began a new suite of RHD flare models with the RADYN code (Carlsson & Stein 1995; in collaboration with M. Carlsson, University of Oslo). Our new simulations use a larger flare heating flux, 10^{12} erg s^{-1} cm^{-2}, and include a gradual phase with the flare heating turned off. We find that the predicted white-light continuum experiences the same shortcomings as the simulations with 10^{11} erg s^{-1} cm^{-2} from Allred *et al.* (2006).

Broadband colors indicate that the peak of the white-light is located in the near-UV; we are seeking to precisely locate the peak and determine the detailed near-UV continuum properties using spectra that extend down to the atmospheric limit. Future work includes analysis of spectra at $\lambda \sim 3200$Å obtained with the South African Large Telescope during a "megaflare" on YZ CMi (in collaboration with B. Brown, University of Wisconsin-Madison, and M. Mathioudakis, Queen's University, Belfast). These observations will provide the next-generation of constraints for more successful RHD models. We are working on advanced RHD models, which include an even larger heating flux and a "stellar-type" flare heating mechanism deduced from X-ray observations reported in Osten *et al.* 2010.

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