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Modeling the Optical (and NUV) Continuum Emission in Stellar Flares

- Report on participation in the Kyoto University Superflare Workshop

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Abstract. This is a report of my visit to Kyoto University in March 2016 for the Superflare Workshop, supported by the International Research Unit of Advanced Future Studies, Kyoto University. The Superflare Workshop was very well attended by all Japanese superflare researchers on stars and on the Sun, and also by many international experts. There were many valuable discussions about the outstanding problems in flare physics that could be addressed by studying superflare stars in the Kepler field. My presentation described recent work in modeling the white light flare continuum radiation on low mass stars and connected to new models of near-ultraviolet spectra of solar flares. There was discussion of future flare observations with the new 3.8m Japanese telescope at Okayama Observatory, and the possibility for international collaboration to obtain high-time resolution, high-spectral resolution Balmer jump observations in preparation for spectra of superflares.

Keywords: stars: flare, stars: activity, Sun: flare

1. The White-Light Continuum Emission in Stellar Flares

During flares, stored magnetic energy in coronal fields is released through magnetic reconnection and retraction. Energy is converted to the kinetic energy of particles, which stream along the reconnected magnetic field lines and deposit their energy into the lower, dense atmosphere (chromosphere and/or photosphere). A large fraction of the radiated energy during a flare is released in the near-ultraviolet and optical (white-light) continuum emission, with a smaller but non-negligible fraction also radiated in the optical and ultraviolet emission lines (Hawley & Pettersen 1991, Osten & Wolk 2015). Several modes of energy transport are thought to link the magnetic energy released in coronal fields and the heating of the lower atmosphere that produces the flare emission. These heating mechanisms include nonthermal particle (electron and proton) precipitation (Emslie 1978), conductive energy transport (Longcope 2014), backwarming via X-ray and ultraviolet radiation (Hawley & Fisher 1992, Allred et al. 2006), and Alfvén wave conversion to nonthermal particles and/or wave energy dissipation (Reep and Russell 2016, Fletcher & Hudson 2008). The white-light continuum emission is thought to originate from the highest densities in the stellar atmosphere; therefore, comparing model predictions of the white-light to observations can be used to critically understand and constrain the role of each of these mechanisms in the flare heating through the impulsive and gradual phases.

In Kowalski et al. (2015), we presented a new M dwarf flare model with heating from a high flux of nonthermal electrons, and we applied a modeling technique of the Balmer edge region ($\lambda \sim 3600$ Å - 3800 Å) that has been developed by the white-dwarf modeling community. The modeling technique provides a new constraint on the charge density that is attained in the continuum-emitting layers in flares for comparison to the predictions of flare heating mechanisms.

2. Modeling Balmer Jump Spectra

In Kowalski et al. (2015), we presented the atmospheric evolution and detailed continuum spectra from a new simulation with the 1D RAYDN code (Carlsson & Stein 1997), which solves the equation of radiative-transfer for a 6-level hydrogen atom, 9-level helium atom, and a 6-level Ca II ion on an adaptive grid. We modeled the energy deposition from a high flux of nonthermal electrons (10^{13} erg cm^{-2} s^{-1} ; F13) using the collisional thick target formulae of Emslie (1978) and Hawley & Fisher (1994). The heating was modeled for 2.3 s, which represents impulsive heating of a single flux tube. In future work, we plan on adding up the emission from individual flux tubes to simulate the emission from a two-ribbon flare as observed on the Sun.

A spectral flare atlas of twenty M dwarf flares was presented in Kowalski et al. (2013), showing a continuum distribution with a color temperature of T~10,000 K and a small Balmer jump ratio in the impulsive-type flare events (see S. L. Hawley's report). We compared the predictions of the F13 model to representative spectra during the impulsive phase of a flare from Kowalski et al. (2013) and found satisfactory agreement with these observed characteristics, which are difficult to reproduce using any other standard flare heating mechanism. Radiative-hydrodynamic models use a simplified treatment of hydrogen for detailed cooling rates, but a comparison to the observations of the spectral region around the Balmer jump requires including the opacities from the higher order lines with overlapping emission wings (Doyle et al. 1988, Hawley & Pettersen 1991). Solar flare spectra covering the Balmer jump spectral region are difficult to obtain with current solar instrumentation (Kowalski, Cauzzi, & Fletcher 2015) but exhibit qualitatively similar characteristics (see Donati-Falchi et al. 1985).

2.1. The Opacity Effects from Landau-Zener Transitions

In flares, the charge density in the chromosphere increases, and the Stark effect causes the energy levels of hydrogen near the continuum to overlap; the theory and modeling techniques for including the opacity effects that result from overlapping Stark states were developed for modeling hot star atmospheres (Hummer & Mihalas 1988, Dappen et al. 1987, Hubeny, Hummer, & Lanz 1994) and are currently employed by state-of-the-art white-dwarf model codes (Trembaly & Bergeron 2009).

We used the NLTE RH code (Uitenbroek 2001) and a 20-level hydrogen atom to calculate the spectrum between $\lambda = 3646 - 4000$ Å where the higher order Balmer lines merge together. For each principal quantum number n, there is a critical electric microfield (due to the distribution of protons in the flare chromosphere) that causes the Stark states of level n to overlap with level $n+1$. At these "avoided crossings" of levels there is a probability that a series of Landau-Zener transitions will occur causing an electron in n to rapidly cascade to the continuum. As a result, photons with $\lambda > 3646$ Å can photoionize hydrogen with an electron in the $n=2$ state. Following Trembley & Bergeron (2009), we modified the Balmer bound-bound and Balmer bound-free opacity and emissivity at $\lambda > 3646$ Å in the RH code to account for these photoionizations. We obtained the atmospheric temperature, velocity, and density from $t=2.2$ s in the dynamic (RADYN) simulation, and we found that the opacity and emissivity from Landau-Zener transitions caused the higher order Balmer lines to fade into Balmer continuum emission that is produced in the model at $\lambda < 3780$ Å.The modeling of the Landau-Zener continuum emission extending redward of $\lambda = 3646$ Å explains the lack of a Balmer edge in high-spectral resolution observations of M dwarf flares (Fuhrmeister et al. 2008) and solar flares (Donati-

Falchi et al. 1985). As a result of our work, this complicated spectral region can be used as a diagnostic of the charge density produced in the flare atmosphere. From broadband colorimetry and spectral observations in the blue-optical regime during stellar flares, we have inferred that the white-light emission originates from large heating at high densities (Kowalski et al. 2013). Modeling the Stark effect and the Landau-Zener transitions results in a new constraint on the density where the white-light emission is produced in order to test proposed flare heating mechanisms (e.g., particle beams, conductive energy transport).

2.2. New Observations of the Balmer Jump Region

New high-temporal resolution observations of the Balmer jump region are needed since the only echelle observations of this spectral region were obtained with an integration time of 15 minutes (Fuhrmeister et al. 2008), which is long compared to the duration of the flare impulsive phase. At the Superflare workshop, we discussed a collaboration to obtain echelle spectra of M dwarf flares at high-time resolution and high spectral resolution in order to test our models of the Balmer jump region, and to compare to spectra that we aim to acquire during super flares on G stars from the 3.8 m telescope at the Okayama Observatory. M dwarfs are known to produce superflares on occasion (Hawley & Pettersen 1991, Osten et al. 2010), and a direct comparison to the flare continuum and line properties will form constraints on heating mechanisms in flares from stars that span a range of mass and dynamo action. In particular, we will be able to compare the charge density in the flare chromosphere during superflares on M and G dwarfs.

3. Future Modeling Directions

In future modeling work, we seek to rigorously test the F13 beam model of M dwarf flares. We will consider the energy loss effects from the return current electric field and model the Balmer lines with an improved theoretical description of the Stark effect. We are also modeling new solar observations of the near-ultraviolet emission lines and continuum from the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014). The chromospheric emission lines from IRIS exhibit complex line profiles (Graham & Cauzzi 2014), which can be explained by dense, heated downflows produced by a large flux of nonthermal electrons. The high-spectral resolution observations of solar flares can be combined with broad-spectral characterization of the Balmer jump and optical region in stellar flares to rigorously test flare heating mechanisms and the standard solar flare model. The heated downflows (chromospheric condensations; Fisher 1989) attain large densities in the solar and M dwarf flare models with high fluxes of nonthermal electrons. The charge density can be critically constrained and compared to these models by measuring the broadening of the Balmer lines and the properties of the continuum emission just longward of the Balmer edge.

An F13 energy flux requires a coronal magnetic field strength of ~1.5 kG (Kowalski et al. 2015). High magnetic fields covering a large fraction of the visible stellar disk have been inferred from Zeeman splitting of optical lines (Johns-Krull & Valenti 1996), but the current knowledge of the coronal field strengths in M dwarfs is poor. Measurements of photospheric magnetic fields of superflare stars using the Zeeman effect would help compare the magnetic environment to active M dwarf stars, and X-ray observations during superflares would help establish an estimate for the coronal field strength (Shibata & Yokoyama 1999). X-ray observations would also help constrain the return-current heating (Holman 2012), which is large in the corona for an F13 electron beam.

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