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Title: Transient Redshifted Emission Lines from Stellar “Magnetic Fireballs”

Background: Solar flares result from the explosive release of energy from stressed, coronal magnetic fields, producing electromagnetic radiation from the radio to the gamma-ray wavelength regimes. Many solar flares have been observed with IRIS, which is a recently launched NASA space observatory to determine how the lower layers of the solar atmosphere are heated. IRIS provides high spectral, high spatial resolution images and spectra of the Sun in the near and far-ultraviolet wavelength regimes. During the impulsive phase of solar flares, bright, mysterious emission components are observed in the red wing in chromospheric (singly ionized) lines [1]. The white-light (continuum) emission also appears prominently in the impulsive phase, but previous observations have not been able to establish the relationship between these phenomena.

We recently completed a detailed comparison of new radiative-hydrodynamic flare models to the observations of the March 29th 2014 X1 solar flare. We used a high flux electron beam to reproduce the bright NUV continuum emission and the red-wing emission component in the chromospheric flare lines. By reproducing both of these phenomena, we have inferred that there are two flaring layers in the chromosphere: 1) a 25 km deep chromospheric condensation (compression) at z ~1000 km and 2) stationary flaring layers extending several hundred km just below the chromospheric condensation. The NUV continuum emission originates primarily from the stationary flaring layers in the first two seconds; at 4 seconds into the simulation, the chromospheric condensation increases in density and dominates the output of continuum radiation. Modeling of these two flaring layers has also reproduced the strength and shape of the redshifts of the Fe II chromospheric emission lines observed in IRIS spectra of the brightest kernels in the March 29th, 2014 flare. In Figure 1, we show the observed NUV spectra (top panel) of the brightest flare kernels compared to the RADYN prediction (bottom panel). The model spectrum (purple curve in bottom panel) adequately reproduces both the Fe II emission at the rest wavelength and the broader emission component (``RWA'') at redder wavelengths (indicated by arrows). This type of line profile has often been observed in spectra of H-alpha during solar flares, and we have found that the chromospheric emission lines and white-light emission can be explained by these two flaring layers with T~10,000 K and $n_e$ ~ 5E13 - 4E14 $cm^{-3}$.

In Figure 2, we show a cartoon of the standard solar flare model with electron beam heating at the footpoints of magnetic loops. The study of the Mar 29th 2014 X1 flare has revealed the existence and properties of the two flare layers below the lower shock of a 10 MK temperature plug in the chromosphere. We loosely refer to atmospheric response in the cartoon as a “magnetic fireball” because in our (1D) modeling the explosive mass motions upward and downward are confined to the magnetic field direction (plasma $\beta < 1$).

Project Description: The goal of this project is to determine if electron beam heating during solar flares explains the bright, redshifted emission components of ultraviolet chromospheric lines that have recently been observed at unprecedented spatial and spectral resolution with the Interface Region Imaging Spectrograph (IRIS). The student will quantify the strength of these red shifted emission components for a sample of flares observed with IRIS and compare to new models of electron beam heating that produce “magnetic fireballs” in the lower atmosphere [2].

References:

[1] Graham, D. & Cauzzi, G. 2015 “Temporal Evolution of Multiple Evaporating Ribbon Sources in a Solar Flare”, *Astrophysical Journal Letters*, 807 22
http://adsabs.harvard.edu/abs/2015ApJ...807L..22G

[2] Kowalski, A. F., Allred, J. C., Daw, A. N., Cauzzi, G., Carlsson, M. 2016, “The Atmospheric Response to High Nonthermal Electron Beam Fluxes in Solar Flares I: Modelling the Brightest NUV Footpoints in the X1 Solar Flare of 2014 March 29”, accepted for publication by the *Astrophysical Journal.*
https://www.dropbox.com/s/5tfnnpda03d309z/kowalski_etal_2016_Mar292014Flare.pdf?dl=0

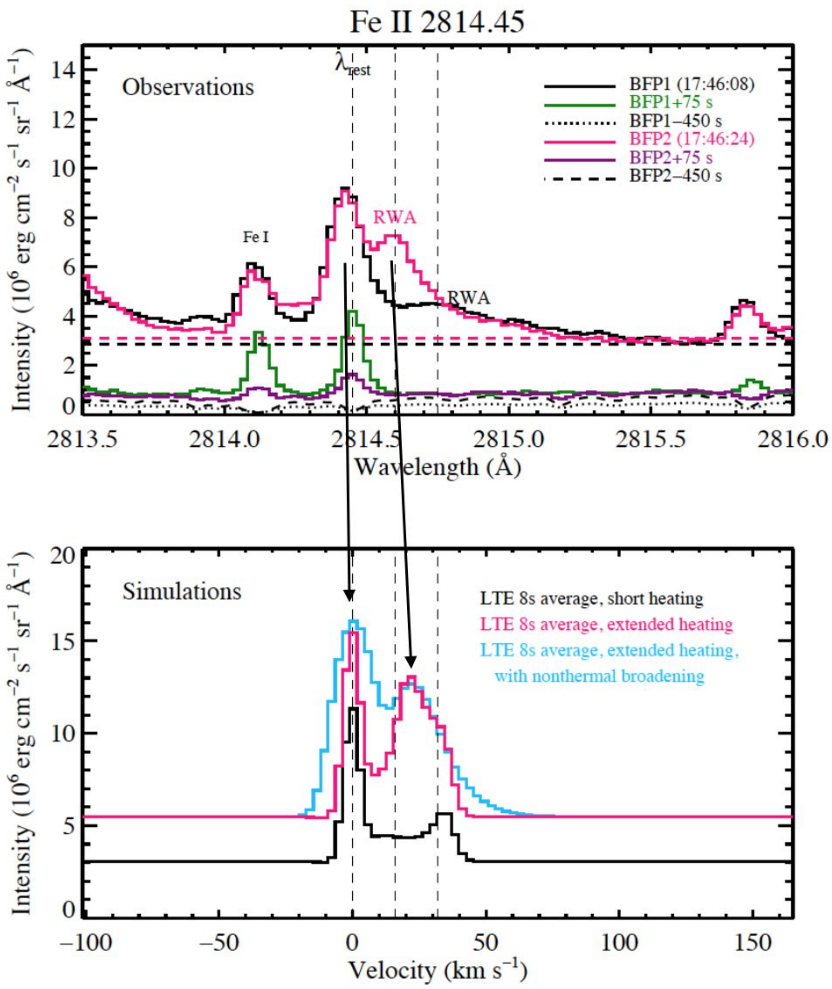


Figure 1 -- *Top:* IRIS near-ultraviolet spectra (black and pink curves) of the brightest kernels in the March 29th, 2014 X1 solar flare, centered around an Fe II emission line. *Bottom:* The predicted continuum and Fe II emission line from our RADYN model (black and pink curves) of the atmospheric response to an electron beam with a large flux. The model successfully reproduces the continuum intensity level and the critical Fe II line profile characteristics. Arrows indicate the similar line profile features in the model and observations; the rightmost arrow indicates the red-wing asymmetry feature (RWA) that is present in all chromospheric lines in this flare. Figure from Kowalski et al. 2016.

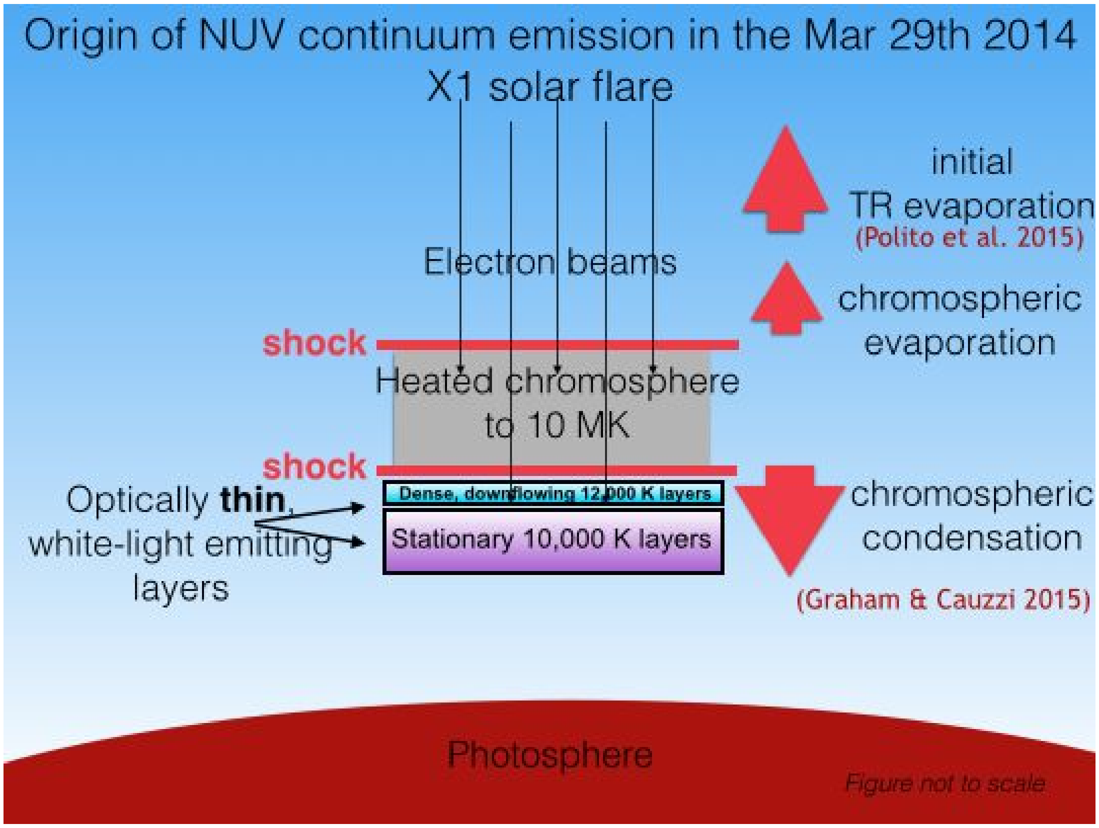


Figure 2 -- Cartoon illustrating the atmospheric response to the heating from a high-flux electron beam. Using IRIS data of the chromospheric (Fe II) emission lines and NUV continuum intensity in the brightest flare footpoints of the 2014 March 29 solar flare, we have inferred that two flaring layers consisting of “dense, downflowing layers” (cyan) and “stationary 10,000 K” layers (purple) are heated just below the site of a 10 MK temperature “plug”. The NUV continuum emission in this flare is primarily spontaneous Balmer recombination radiation formed over low optical depth in these two flaring layers. Cartoon has been adapted from the Kowalski (2015) model M dwarf flare atmosphere.