White Light Sources in the 15th Feb 2011 Solar Flare

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Introduction and Motivation

White light (WL) solar flares show enhancements in the optical continuum emission, but being observational rarities, and consequently understudied events, the mechanism responsible for this continuum enhancement is still not comprehensively known or understood.

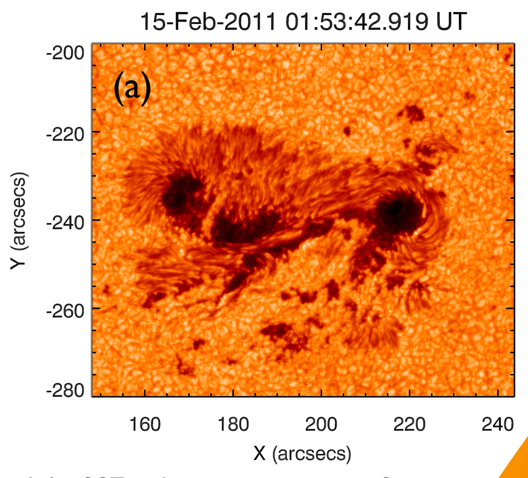
A significant proportion of flare energy is emitted as WL *(Neidig 1989, Fletcher et al 2007)*, and recent studies suggest that WL enhancements are actually common to most flares *(Kretzschmar 2011)*, no longer being seen as a 'big flare phenomenon'. To have a comprehensive understanding of flare physics and energy transport, the mechanism responsible for, and the properties of, WL flares must be understood.

Using ***Hinode*/SOT RGB** filter data from the **15th Feb 2011 X2.2 class flare** we identified WL continuum enhancements, and investigated the characteristics of WL sources under the assumptions of two simple models, in order to assess the validity of:

(1) a photospheric blackbody source or **(2) a chromospheric free-bound source**

We identify WL sources as described by the process in the panel opposite, and select two examples (one from each flare ribbon) to illustrate the properties of WL emission from this flare. All results presented here are from these two examples sources.

See Kerr & Fletcher (2013) for more details.



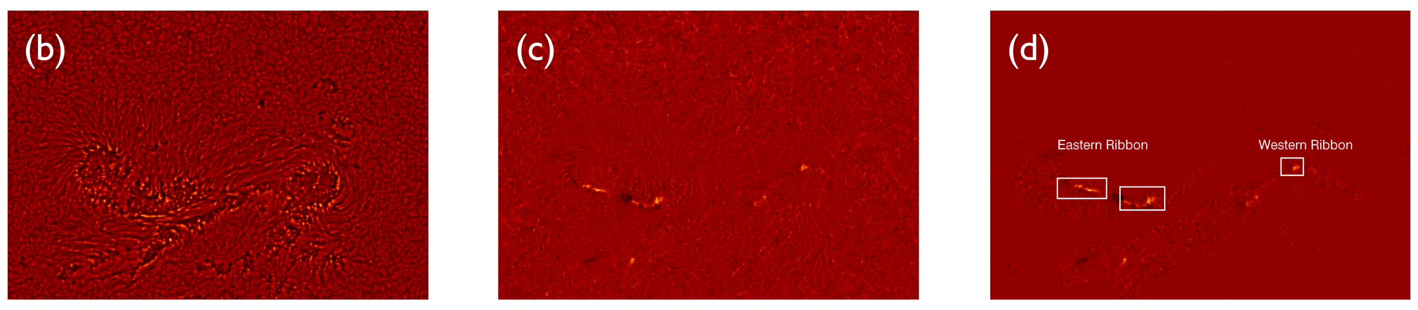
a) An SOT red continuum image of the flaring region.

There were SOT observations in **RGB** between ~01:50UT and ~01:59UT, with a cadence of ~19-21s in each filter.

Finding White Light Sources

Bright photospheric background makes WL flare enhancements difficult to detect, and granulation results in noisy difference images. Images were log-unsharp filtered before performing running differences. Flaring sources were identified by finding the local mean and standard deviation (σ) inside small pixel groups, setting 1, 2 or 3-σ as thresholds. Data were calibrated using SOT responses calculated for each channel *(T. Tarbell, private comm.)*, converting $\mathrm{DN\ s^{-1}}$ to $\mathrm{W cm^{-2} sr^{-1} Å^{-1}}$.

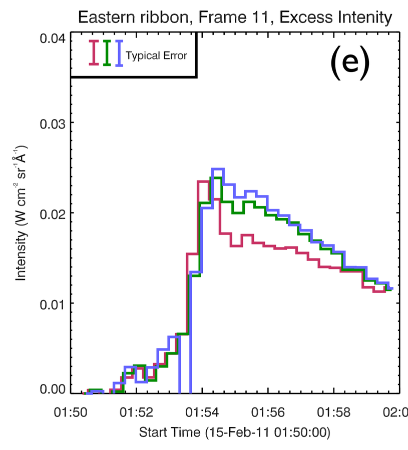
b) Filtered image
c) Running difference
d) Selecting the impulsive WL pixels

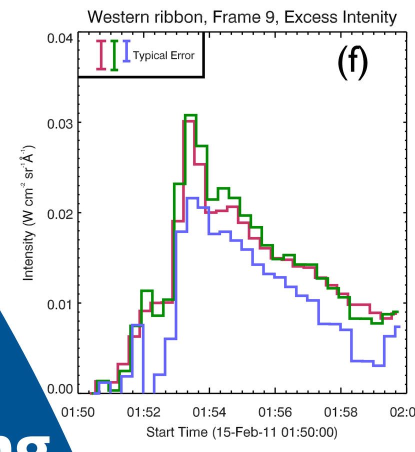


This method identifies WL pixels that are newly brightened in Frame *i*. The central figure in this poster shows the WL sources with colour indicating the time of first detection. We selected sources first identified in Frame 11 in the eastern ribbon, and Frame 9 in the western ribbon, as examples to illustrate the properties of WL enhancements during the flare. It is the results from these frames that are presented here.

e) Flare emission from pixels identified as first brightening in Frame 11, eastern ribbon

f) Flare emission from pixels identified as first brightening in Frame 9, western ribbon





Photospheric Blackbody Model

Model Description

An optically thick source in the photosphere is locally heated by some ΔT following a flare, producing an enhanced blackbody spectrum. This model assumes no chromospheric contribution to the optical continuum enhancements.

Effective Temperature

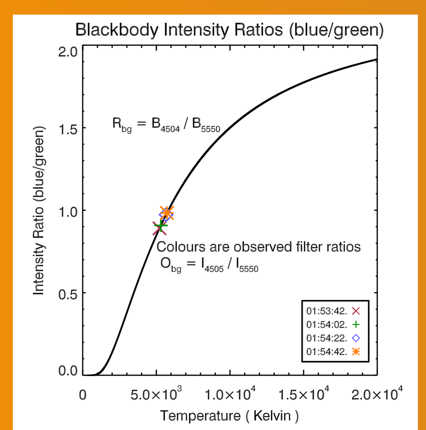
χ^2 goodness-of-fit tests gave the best-fit effective temperature in each source.

χ^2_λ values were calculated for each SOT channel at temperatures in the range $T \in [0, 20000]$ K. The temperature which minimised the total χ^2 was the effective temperature, T_e. These temperatures are represented as black diamonds on the plots below, showing a temperature increase of ~200K.

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{\exp\{\frac{hc}{\lambda k_b T}\} - 1}$$

Colour Temperature

WL source colour temperatures measured using filter ratio method. Blackbody intensity as a function of temperature calculated for each SOT **RGB** wavelength. Filter ratio of two channels produces a temperature dependent curve. Observed **RGB** filter ratios were then measured and compared with the theoretical curves, giving a measurement of the colour temperature.



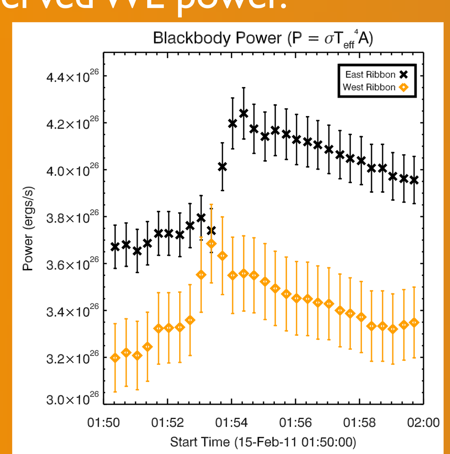
$$R_{b/g}(T) = \frac{B_{4504}(T)}{B_{5550}(T)} \text{ Vs } O_{b/g} = \frac{I_{4504}}{I_{5550}}$$

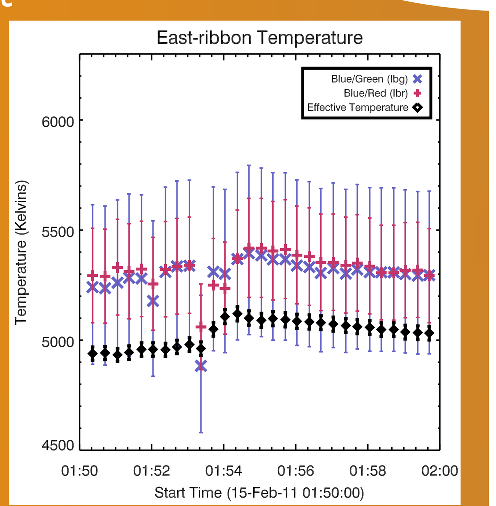
Typically $\Delta T \approx 200$ K

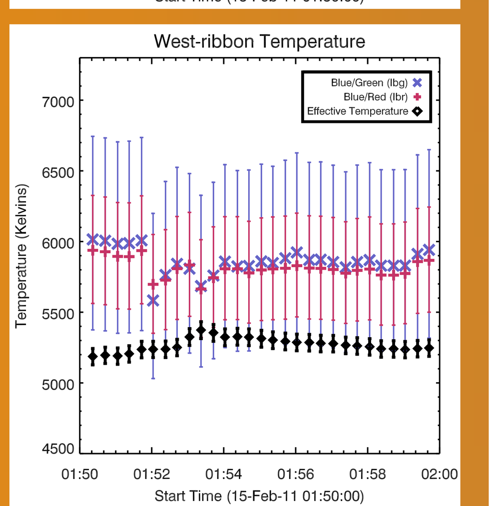
WL Source Properties

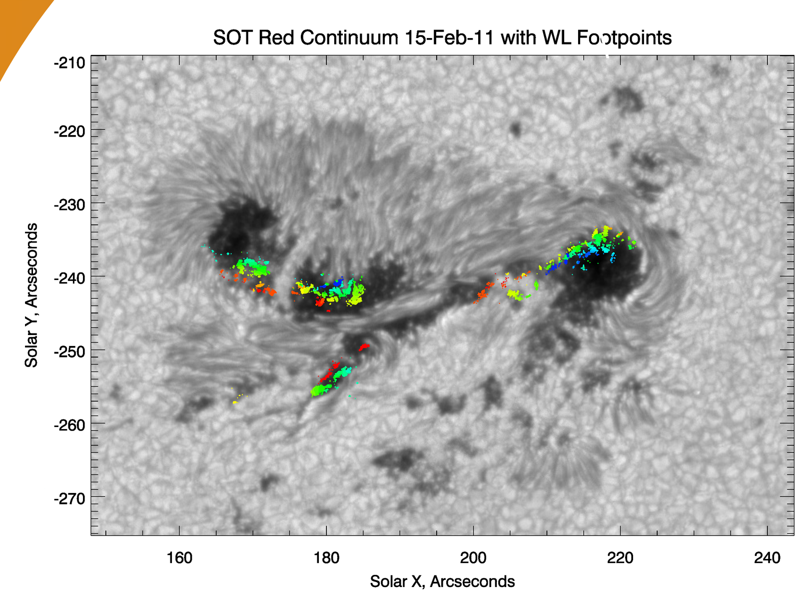
In the eastern ribbon, the colour temperatures are consistent within the errors to the effective temperature. This is more ambiguous in the western ribbon.

From these temperatures, the power radiated in WL in the blackbody assumption can be calculated, which was $P = \sigma A T^4 \approx 10^{26}$ ergs s^{-1}. This compares well to the observed WL power.









Flare sources as a function of time.

***HINODE*/SOT** optical continuum measurements from RGB filters:

6684 Å 5550 Å 4504 Å

Chromospheric Free-Bound Model

Model Description

Consider an optically thin slab of material in the chromosphere that is overionised and heated during the flare, leading to enhanced recombination radiation with intensity defined by Eq [1] *(Kowalski 2012, Aller 1963)*.

$$I_{\lambda,\mathrm{fb}} = \left[\frac{6.48\times10^{-14}}{4\pi\lambda^2}\right]\left[\frac{n_e^2 T^{-3/2}}{n^3}\right]\exp\left\{\frac{1.58\times10^5}{n^2 T} - \frac{1.44\times10^8}{\lambda T}\right\} \quad \text{[Eq 1]}$$

$I_{\lambda,\mathrm{fb}}$ - Intensity, T - Temperature, L - Slab thickness, n_e - Density, n - Principal quantum number of level that electron recombines to

Assumes isothermal temperature, $n_e = n_i$ and that this is the only source of enhanced WL emission.

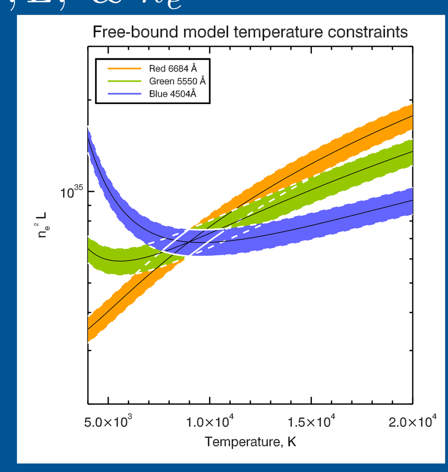
Constraining Temperature

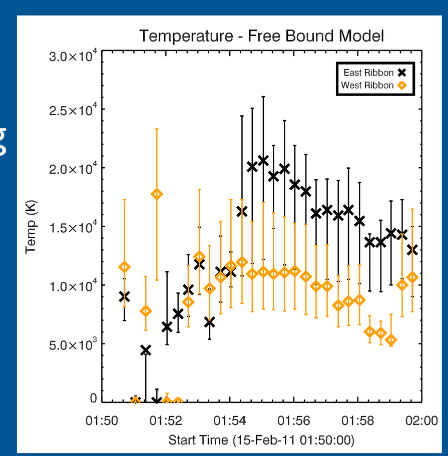
[Eq 2]

$$n_e^2 L = \frac{4\pi\times10^{14}\lambda^2}{\exp\left\{\frac{1.58\times10^5}{n^2T} - \frac{1.44\times10^8}{\lambda T}\right\}}\frac{n^3 T^{3/2} I_{\lambda,\mathrm{fb}}}{6.48}$$

Three unknown parameters in Eq [1] : $T, L, \ \& \ n_e$

We constrain these parameters to see if the model produced reasonable values. Rearranging Eq[1] gives Eq[2]. Background subtracted SOT intensities were used in Eq [2] and the value $n_e^2 L|_{\mathrm{obs}}$ was computed as a function of temperature. An area of overlap between the three filters was found, constraining temperature to a range $T \approx [5500, 25000]$ K typically peaking at $T \approx 20000$ K.

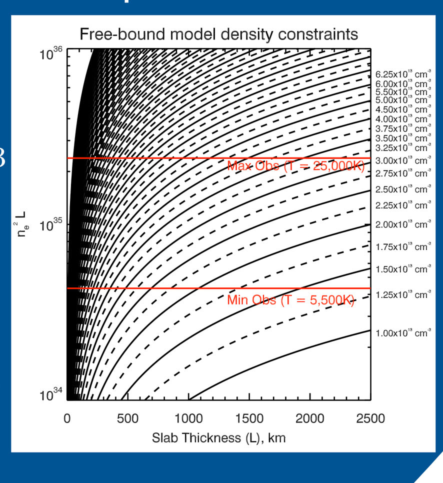




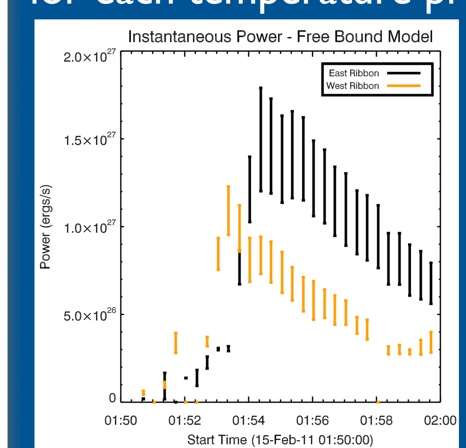
Shown right are temperature profile for example sources: Frame 11 in eastern ribbon, Frame 9 in western ribbon

Density and Power

Plotting model curves of $n_e^2 L|_{\mathrm{model}}$, it is possible to place constraints on the density of the slab. Slab thickness is not known, but reasonable to assume that slab is somewhat less than 500 km thick. Density is constrained $n_e = 10^{(13-14)}$ cm^{-3}



Power was measured by integrating under the free-bound spectra created for each value of temperature in the overlap region, with the upper and lower limit of $n_e^2 L|_{\mathrm{obs}}$ for each temperature providing limits.



Typical powers on the order 10^{27} ergs s^{-1}

Conclusions

Photospheric Blackbody Model:

-Colour temperature and effective temperature largely consistent within the errors of the data for the eastern ribbon, suggesting that the source has blackbody properties.

-The east ribbon may have a more dominant blackbody component than the west ribbon, which shows more ambiguous properties.

-The power in *each SOT channel* was measured as $\approx 10^{23}$ ergs s^{-1} which when extended over the whole WL spectrum is consistent with the power output under the blackbody model assumptions of $\approx 10^{26}$ ergs s^{-1}

-*However*, we do not know how to get flare energy down to the photosphere to produce this heating.

Chromospheric free-bound model:

-Parameters were constrained to suggest a peak temperature of around , $T \approx 20000$ K with a range $T \approx [5500, 25000]$ K , and a density of $n_e = 10^{(13-14)}$ cm^{-3}, suggesting a slab in the lower chromosphere. The power radiated is an order of magnitude greater than that radiated in the blackbody model (and the observations).

-Easier to imagine direct flare effects in these higher layers, but the model ignores any photospheric enhancement from backwarming or other means (bearing in mind that photospheric enhancements implied by blackbody model).

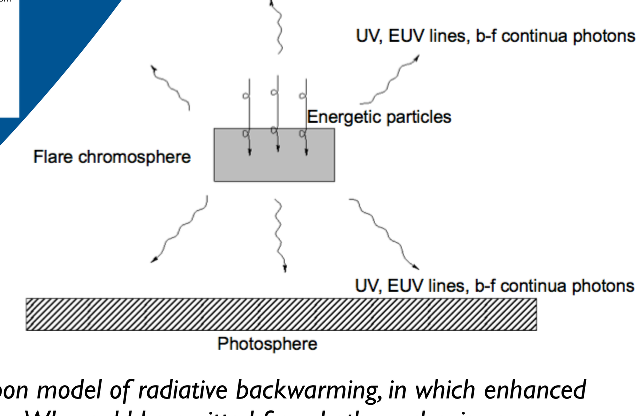
Combination of Mechanisms?

Likely that both blackbody and recombination mechanisms lead to WL flare emission. The relative contribution could vary from flare to flare.

Possible to heat the photosphere via radiative backwarming, following recombination emission in the chromosphere. It has also recently been shown that the temperature minimum region (TMR) can be heated by Alfvén waves *(Russell & Fletcher, 2013)*.

This heating would then result in an enhanced blackbody intensity, in combination with enhanced recombination emission.

Advanced modelling (e.g. using RADYN, *Allred et al (2005)*) of these processes will improve this study.



Cartoon model of radiative backwarming, in which enhanced WL would be emitted from both mechanisms

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