Understanding Alfvénic Waves in Flares

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1 Introduction

Solar flares are driven by the release of magnetic energy from reconnection events in the solar corona, whereafter energy is transported to the chromosphere, heating the plasma and causing the characteristic radiative losses. In the collisional thick-target model (CTTM) [Brown 1971, Hudson 1972], electrons accelerated to energies exceeding 10 keV traverse the corona and impact the chromosphere, where they deposit their energy through collisions with the much denser plasma in the lower atmosphere. While there are undoubtedly high energy non-thermal electrons accelerated in flares, it is unclear whether these electron beams are the sole mechanism of energy transport, or whether they only dominate in certain phases of the flare’s evolution. Alfvénic waves are generated during the post-reconnection relaxation of magnetic field lines [Guidoni and Longcope 2010, Longcope and Tarr 2012], so it is important to examine their role in energy transport.

Emslie and Sturrock (1982) proposed that Alfvénic waves, produced in the corona and traveling downwards in the solar atmosphere, can sufficiently explain observed heating at the temperature minimum region in large flares. More recently, Fletcher and Hudson (2008) proposed that these waves were able to transport the released magnetic energy to heat the entire chromosphere, and accelerate electrons in situ in the chromosphere, thereby producing the characteristic hard X-ray (HXR) emission of flares. Using the formalism of wave dissipation developed by Emslie and Sturrock (1982) and Russell and Fletcher (2013), Reep and Russell (2016) showed that high frequency Alfvénic waves can heat the upper chromosphere, and produce an atmospheric response that is strikingly similar to the CTTM. This result was confirmed by Kerr et al. (2016), who concluded that despite the superficial similarities, the two mechanisms could be distinguished in chromospheric emission lines such as the Mg II k line. These predictions have never been tested directly with observations.

Both Reep and Russell (2016) and Kerr et al. (2016) found that wave frequencies \( \geq 1 \) Hz strongly heat the upper chromosphere. It is not known at present what Alfvénic wave frequencies might occur in solar flares, although mHz waves are seen ubiquitously in active regions [Tomczyk et al. 2007, McIntosh et al. 2011]. Waves with frequencies as high as 0.1 Hz were observed with TRACE [DeForest 2004], while 1 Hz waves have been seen in coronal lines during total eclipses [Pasachoff et al. 2002]. Models of magnetohydrodynamic waves in arcades do predict the presence of Alfvén waves with frequencies higher than 0.1 Hz (e.g. Oliver et al. 1993), although they have not yet been observationally confirmed. In order to resolve frequencies \( \geq 1 \) Hz, an imager with cadence of \( \leq 1 \) s is required.

An important consideration is non-thermal line broadening, commonly observed in flares, which may be attributable to unresolved wave motions. For example, Milligan (2011) measured line widths in two Fe XIV lines during a small flare with Hinode-EIS, and found a large non-thermal component \( (\approx 50 \text{ km s}^{-1}) \) that could not be explained by opacity or pressure broadening. Polito et al. (2013) similarly found large non-thermal velocities in strongly blue-shifted Fe XXI emission measured with IRIS. The role of wave motions in producing non-thermal line broadening could be ascertained with spectra at a cadence high enough to resolve these wave motions.

2 Proposed Instrumentation

A spectrometer with a cadence of less than 1 s and spectral coverage of the transition region (TR) and chromosphere could measure this energy transport. Specifically, by measuring spectral lines from ions of many ionization stages and formation depths, the transport of energy could be followed through the impulsive phase of a solar flare, strongly constraining our models of energy release. In order to resolve the waves, high cadence imaging is similarly required.

In this white paper, we therefore propose that these questions could be examined with an improved slit spectrograph with an explicit aim towards extremely high cadence spectra in the extreme ultraviolet range, which can only be seen from space. The instrument should be designed to (1) measure the depths of energy deposition, (2) measure the travel times between these depths, (3) resolve high frequency waves, and (4) discriminate the atmospheric response between electron beams and Alfvén waves. A slit-jaw imager, whereby light surrounding the slit is reflected onto broadband filters (e.g. IRIS, De Pontieu et al. 2014), with extremely high cadence of \( \approx 0.1 \) s could suitably resolve high frequency wave motions. Finally, to measure information about the non-thermal electron population, a hard X-ray spectrometer (e.g. MinXSS, Mason et al. 2016), which need not have spatial resolution,

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\[ \text{Science Objective: Understanding Energy Transport by Alfvénic Waves in Solar Flares} \]

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Figure 1: The electron density along a flare loop in a simulation of Alfvénic wave heating (top) and electron beam heating (bottom), at three select times. As the wave pulse propagates through the chromosphere dissipating its energy, the local temperature rises, causing an increase in the ionization of hydrogen, which in turn increases the electron density at ever-increasing depths. Contrast this with the beam case, where the increase in electron density occurs at approximately the same depth during the early impulsive phase. The local flow-speed velocity is colored blue where material is up-flowing and red where it's down-flowing. The dotted lines indicate the initial density. The x-axis is displayed on a logarithmic scale to emphasize the chromosphere.

could supplement these observations to determine the presence of non-thermal electrons via bremsstrahlung signatures and estimate their energy distribution, as well as giving estimates of the flaring loop temperatures from thermal continuum emissions.

The magnetic field strength and structure determines how waves will propagate through the plasma, and to determine this we plan to rely on coordination with the current and next generation of ground-based solar telescopes, specifically the Daniel K. Inouye Solar Telescope (DKIST, Elmore et al. 2014, expected first light 2019) and European Solar Telescope (EST, Collados et al. 2013, expected first light 2026), both currently under construction. The instrument suites at these facilities will complement our proposed observations with very high spatial and temporal resolution measurements of chromospheric lines and magnetic field structure. The current generation of ground–based instrumentation already makes routine polarimetric observations of photospheric and chromospheric lines (e.g. Fe I 6302 Å and Ca II 8542 Å, Keller et al. 2003) from which the magnetic field is determined by inversion using an ever-expanding set of techniques (e.g. Sankarasubramanian et al. 2006).

DKIST will break from previous ground-based solar telescopes by implementing a queue system for observations which will allow for increased target–of–opportunity observations to be collected, e.g., during flares. Temporal cadence of observations is limited by the camera speed, but will surpass what we propose for the satellite observations. For instance, DLNIRSP camera speed is ~ 33 ms, and the small FOV (5′′ × 5′′) may be tessellated, with each step requiring an addition 50 ms, so that a 25′′ × 25′′ FOV may be generated in as little as 2 s. This is at the highest resolution, which is not always necessary. Furthermore, the spectroscopic instruments of DKIST—DLNIRSP and ViSP—are designed to be used simultaneously, and to each individually measure several spectral windows simultaneously. Their addition of visible and infrared wavelengths at very high spatial, temporal, and spectral resolution will compliment our proposed EUV mission to determine where, and by what mechanism, energy is deposited during flares.
3 Simulations

We briefly present numerical simulations performed with the HYDRAD code (Bradshaw and Mason, 2003; Bradshaw and Cargill, 2013), adapted to include heating by a beam of electrons or heating due to the dissipation of Alfvénic waves. A 10 keV electron travels at \( \approx 60 \text{ Mm s}^{-1} \), so we neglect travel times for electron beams in general. However, waves travel at the Alfvén speed, which is often \( 5-10 \text{ Mm s}^{-1} \) in the corona, though considerably less in the chromosphere, so time delays in wave heating cannot be neglected. The simulation presented here has modified the code used in Reep and Russell (2016) to therefore trace the location of the waves with time.

Figure 1 shows the electron density evolution in an example simulation of heating by Alfvénic wave dissipation (top plots). The wave pulse, injected at the apex of the loop, propagates downwards at the Alfvén speed (\( \approx 9 \text{ Mm s}^{-1} \) in the corona), reaching the chromosphere in approximately 3 seconds. The local increase in density drives an increased dissipation of the wave via ion-neutral and electron-ion collisions, which in turn heats the ambient plasma. The heat deposition raises the temperature, which in turn raises the electron density as the hydrogen ionization fraction increases, and drives evaporation and condensation flows due to the local pressure expansion. The wave pulse continues to propagate downwards, similarly dissipating its Poynting flux at even greater depths. These plots can be contrasted with an electron beam heating simulation (bottom plots). The electrons reach the chromosphere essentially instantly, where they are stopped due to collisions with the ambient plasma. The depth at which this occurs is approximately constant, and it does not propagate to deeper depths, unlike the wave heating case.

The depth at which heat is deposited therefore can discriminate between these two mechanisms. To measure this precisely, observations of chromospheric lines that form at varying depths at high cadence are required. Kerr et al. (2016), for example, showed that Mg II and Ca II respond differently to wave heating and electron beam heating in the mid chromosphere. We add the example of Lyman-\( \alpha \) to this, shown in Figure 2 calculated from the same simulations and with the same methodology of Kerr et al. (2016). Lyman-\( \alpha \) forms primarily at the top of the chromosphere, with the Lyman continuum formed at slightly lower heights (Vernazza et al., 1981; Carlsson and Stein, 2002). The RAISE sounding rocket (Laurent et al., 2016) has recently demonstrated the viability of observing this line at a cadence \( > 5 \text{ Hz} \).

Therefore, in order to (1) measure what frequency waves occur in flares, (2) trace the location of heating in the chromosphere, and (3) distinguish heating mechanisms, a high cadence spectrograph with a bandpass centered on important chromospheric lines with imaging capability via a slit-jaw imager would be the ideal instrument. The following lines offer good chromospheric and TR coverage and are intense enough to observe at high cadence: Lyman-\( \alpha \), Lyman-\( \beta \), He I 584.3 Å, He II 303.8 Å, Mg II h and k, Si II 1194.5 Å and 1264.7 Å. In combination with the optical lines measured with DKIST and EST, the motion of magnetohydrodynamic waves through the chromosphere can be traced so that the role of waves in flares will be understood.
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