Solar flares are a fundamental component of solar eruptive events (SEEs; along with solar energetic particles, SEPs, and coronal mass ejections, CMEs). Flares are the first component of the SEE to impact our atmosphere, which can set the stage for the arrival of the associated SEPs and CME. Magnetic reconnection drives SEEs by restructuring the solar coronal magnetic field, liberating a tremendous amount of energy which is partitioned into various physical manifestations: particle acceleration, mass and magnetic-field eruption, atmospheric heating, and the subsequent emission of radiation as solar flares. To explain and ultimately predict these geoeffective events, the heliophysics community requires a comprehensive understanding of the processes that transform and distribute stored magnetic energy into other forms, including the broadband radiative enhancement that characterises flares.

This white paper discusses energy transport during the impulsive phase of flares. We discuss the gradual phase in a related white paper. Following [1] our approach to solar flare research from now until 2050 reflects the following basic philosophy: (1) to identify the sites of energy release and particle acceleration in the solar corona; (2) to characterize the most energetically important components as they evolve in time and space; and (3) to understand how energy is transported and dissipated, heating the Sun's atmosphere from photosphere to corona. Observations should be made of these energy conversion sites before, during, and after the event, to characterize the magnetic fields, plasma density, temperature, flow velocities, wave fields, and the accelerated electrons and ions. These properties should be measured as close to the release site as possible, both in space and in time to minimize uncertainties due to propagation effects and temporal evolution.

Our aim should be to ensure that models can reproduce fundamental and universal aspects of flares, and to improve the included physics where they cannot. Only then can we hope to model specific flare events. We must determine the acceleration mechanism and propagation properties of accelerated electrons. We must also push beyond the standard paradigm of energy transport via electron beams, particularly to address the roles of flare-accelerated ions, and Alfvén waves. To determine whether these models accurately represent the wide range of flare phenomena, we must confront them with high-quality observations. We outline key areas where progress would advance insight into flare physics substantially.

2 Nonthermal Electrons

Nonthermal electrons are thought to be the primary means by which flare energy is transported through the solar atmosphere. Though great strides have been made, both observationally and theoretically, in our understanding of flare-accelerated electrons, the following fundamental questions must be addressed: (1) where and on what time scales are electrons accelerated, and what is their energy distribution?; and (2) how do the accelerated electrons propagate from their coronal acceleration site to the chromosphere and into interplanetary space? Electron acceleration. Several flare-acceleration mechanisms have been proposed, which differ in the locations and physical processes involved. Candidates include acceleration by electric fields at reconnection sites, contracting or merging magnetic islands along the current sheet, reconnection outflow jets, termination shocks or stochastic acceleration at the top of flare arcades, and large-scale and turbulent parallel electric fields, e.g., through kinetic Alfvén waves (see review by [2]). Establishing the locations (both coronal and footpoint sources), timescales, progression, and spectral characteristics of X-rays can discriminate among these acceleration mechanisms.

Electron propagation and energy deposition. Efforts to explain the shape of X-ray spectra in terms of electron propagation [3, 4] or acceleration [5] have proven fruitful. Features such as strong breaks, though, prove difficult to explain by current propagation models [6, 7]. Many factors affect the transport of electrons from the acceleration region and, consequently, where and how much energy is deposited in the flaring atmosphere. For example, some propagation processes heat the corona, or result in trapping of electrons.

These questions persist in part because present observations of hard X-ray (HXR) and microwave emission (MW), the signatures of electron acceleration, lack the dynamic range to access acceleration sites in the corona in the presence of the much brighter footpoint emission. Emissions at both locations are needed for an accurate characterisation of acceleration processes. To make progress discriminating between spectral features of the acceleration and propagation mechanisms, we require high spectral and temporal resolution (\(\sim 1\) s) X-ray observations over an energy range at least up to 200 keV, with dynamic range (> 100 : 1) sufficient to detect both regions. Imaging spectroscopy of the thermal plasma is needed to differentiate among mechanisms that yield heated coronal plasma: directly by the reconnection process; by the beam losses themselves (including Ohmic dissipation of the beam-neutralising return current); and by chromospheric ablation.
While we wait for more direct proton beam observations via γ-rays, we should use computational experiments to establish the fraction of the flare energy in accelerated ions, the distribution function of those ions, and their spatiotemporal relation to flare accelerated electrons is the best way to test acceleration models and drive flare heating models. For ions > 1 MeV, these properties should be determined from γ-ray observations, for example of the 2.223 MeV neutron-capture line, nuclear de-excitation lines between 1 – 10 MeV, and the positron-annihilation line at 511 keV. These observations can provide the flux and spectral distribution of the highest energy ions. Simultaneous observations of X-rays and γ-rays < 10 keV to > 15 MeV are required to address the relation between electrons and ions.

Flare-accelerated ions < 1 MeV can be revealed by nonthermal Lyα (or Lyβ) wing asymmetries that carry information about the flux, energy spectrum, and direction of the incident protons. These emissions are produced by precipitating nonthermal protons that capture an electron from a neutral hydrogen atom (charge exchange), yielding nonthermal excited neutral hydrogen that subsequently emits a Doppler-shifted Lyα photon. Red-wing enhancements result from photons directly escaping upwards, and blue-wing enhancements result from downward-directed photons that are then scattered by neutral hydrogen. This spectral signature has not yet been observed on the Sun (owing largely to the paucity of Lyα flare observations), but has been observed in terrestrial aurora. A search for asymmetries in the wings of He ii 304 Å, caused by charge exchange with nonthermal α particles, failed to detect this effect, although previous theoretical investigations predicted that the effect should have been detectable. The estimated intensity of these signatures should be revised by flare codes capable of modelling the time-dependent, propagating proton/ion distribution with realistic ionization stratification.

4 Alfvén Waves

Magnetohydrodynamic (MHD) waves are undoubtedly produced in the corona during the large-scale restructuring of the magnetic field during flares. Downward propagating Alfvén waves may heat the lower atmosphere via Joule dissipation of currents or ion-neutral friction. Energy transport by Alfvén waves is well established in the
magnetosphere [see reviews by 36, 37], but their role in solar flare energy transport remains a mystery. A non-trivial amount of the energy could be partitioned into Alfvén waves, a possibility that demands exploration.

High-frequency \( f \gtrsim 1\,\text{Hz} \), to penetrate through the transition region [35]) downward propagating Alfvén waves have received renewed attention as a potential vehicle to transport energy from the coronal energy release site to the chromosphere or deeper [35, 38], and even as a means to accelerate electrons locally in the chromosphere [38]. Several numerical experiments have explored their ability to heat the temperature-minimum region and the chromosphere, and have searched for observational signatures [39–41]. Those pioneering models are rather simplified, however, using (radiation) hydrodynamic codes to model the heating resulting from an approximated form of monochromatic Alfvén waves.

Despite these approximations, such studies have demonstrated that Alfvén waves could efficiently heat the lower atmosphere, and produce mass flows consistent with observations; in addition, varying the wave parameters could heat different locations in the atmosphere, depending on the ionization stratification. However, the lack of definitive observational constraints on wave parameters has severely hampered efforts to make further progress. To determine whether downward propagating Alfvén waves play a significant role in flares, we need to focus on the following areas.

To address this question properly, radiative MHD simulations of flares must include an accurate NLTE chromosphere. However, a radiative MHD flare simulation that resolves the required spatial scales (down to meters in some situations) and incorporates energy transport via nonthermal particles is a challenge that may not be fully realized before 2050. To address this question, we may start with improvements to existing radiation hydrodynamic models, for example by implementing realistic wave spectra and propagation. On the longer term, we should aim to develop a full radiative MHD flare simulation capable of resolving Alfvén wave transport and dissipation and also of modeling the effects of nonthermal particles. The required spatial and temporal scales, and the range of physics processes to be included, make this a very challenging task.

Observational efforts should focus on confirming the presence of these high-frequency waves in the chromosphere, measuring their properties, and determining where they originate and deposit their energy. This will require high cadence (sub-second) and high spatial resolution (less than 0.1") spectroscopy of both the chromosphere and corona. Because the waves propagate deeper through the chromosphere on timescales of a few seconds, emission forming at varying depths could switch on sequentially, requiring broad temperature coverage of spectral lines. Measurements of nonthermal line broadening from spectral lines observed at a series of heights can be used to estimate the energy flux carried by the propagating waves [e.g., 42, 43]. The amount of energy carried by the waves depends on the magnetic-field perturbations, so the coronal magnetic-field fluctuations must be measured to the level of a few percent. The height dependence of the magnetic field and density stratification define the Alfvén speed, an important quantity for models to include accurately. Even a coarse observational sampling of the field strength at different heights would help, which could potentially be provided by the Daniel K. Inouye Solar Telescope (DKIST).

The flare community would benefit here from collaboration with the magnetospheric community. The generation, propagation, and dissipation of Alfvén waves in the magnetosphere during reconnection is a well-established research area [36, 37] that benefits from in-situ measurements. Although the characteristic plasma scales of the solar atmosphere and the magnetosphere differ substantially, for the most part, closer collaboration between flare and magnetospheric researchers would greatly advance our understanding of energy partitioning between particle acceleration and wave generation, the potential energy spectra of Alfvén waves, and pertinent wave-particle interactions.

**References**

[21] Hiei, E. 1982, SoPh, 80, 113
[27] Ishimoto, M., et al. 1989, GRL, 16, 143