Observations and modeling of flare chromospheres

A proposal for an ISSI International Team

Lyndsay Fletcher (Glasgow)

One Page Summary

Solar flares are the most energetic energy release events in the solar system. The majority of energy radiated from a flare originates in the solar chromosphere, the dynamic interface between the Sun's photosphere and corona, and it is only by thoroughly probing the flare chromosphere that we can understand the way in which flare energy is transmitted and dissipated. Over the last few years, observations have become available which provide new constraints on energy deposition, and new tests for the flare models. Advanced numerical simulations can be run which, together with the observations, can constrain the energy input and dissipation during the flare. Within the year, a new satellite observing in the UV will be launched (IRIS) which will allow us the first look at flare radiation in three UV spectral bands not accessible for flare observations since the Solar Maximum Mission three decades ago.

We propose an International Team to take advantage of the present confluence of high quality chromospheric flare observations and sophisticated numerical simulation techniques to push forward on four well-focused questions in flare chromospheric physics. Several members in the proposed international team have already participated in a successful ISSI team (2009-2011), which surveyed the state of the field of flare chromospheric physics, and carried out a number of studies in optical and EUV. Based on the work of this previous team, the following topics are proposed:

- The existence of time-varying hydrogen and helium recombination continua has now been clearly demonstrated in both solar and stellar flares; how do these constrain the ionisation and recombination properties of the flare chromosphere?
- How do we learn about the vertical structure, in temperature, density and ionisation, of the flare chromosphere, from new and existing optical and EUV spectral line diagnostics?
- Are the predictions of electron-beam heated radiation hydrodynamic models consistent with observations? How might these models need to be updated to explain new observed features?
- What should the main scientific goals be for flare studies in the ultraviolet with the Interface Region Imaging Spectrograph (IRIS) satellite and future large ground-based telescopes?

By combining the most up-to-date observations with simulations run for a range of input parameters we will develop a clear picture of the physical structure of the flare chromosphere, and the characteristics of the energy input necessary to explain it.

We propose a series of three meetings to develop and execute joint research programmes on the above topics. The team will consist of 11 members plus two young scientists, and will include theoreticians expert in flare radiation hydrodynamics, non-equilibrium processes and spectral synthesis, and observers specialised in the many space-based and ground-based instruments and techniques relevant to this proposal.

The previous ISSI team produced a number of joint publications, both refereed and non-refereed (see previous team page at ***http://www.issibern.ch/teams/solarflares/***), a chapter in a PhD thesis, successful solar observing runs, as well as an elevated awareness of the importance of flare chromospheres in general via a session (awarded competitively) at the 16th Cambridge Cool Stars workshop, and input to NASA's decadal survey. Based on this past performance, a continued output of refereed journal articles can be expected, as well as new sets of tailored multi-wavelength observations of solar flares.

Observations and Modeling of Flare Chromospheres: Scientific Rationale

Solar flares are epochs of sudden and dramatic release of stored magnetic energy in the solar atmosphere. The first recorded observation of a solar flare just over 150 years ago was made in the visible part of the spectrum (Carrington 1859), and was what we would now term a chromospheric flare. For many decades flares were known only as chromospheric phenomena, with Hα radiation being the primary diagnostic for the physical processes taking place. The characteristics of solar chromospheric flares still puzzle us.

The general problem of the dissipation of stored magnetic energy exists throughout much of astrophysics. In the case of solar or stellar flares (and also coronal heating), it is well established that sufficient *energy* is present in the currents (AC or DC) existing in a stressed, magnetised atmosphere to explain the observed phenomena, but the physics of transporting and converting this energy, into the chromospheric radiation and the fast particles that characterise a flare, is far from clear. In solar and stellar flares, the release and conversion process is so extreme (due to the large quantities of energy being released and radiated in a short timescale and a small volume) that emission is present across the entire spectrum, allowing many independent diagnostics of the same process.

Understanding the energy transport and conversion requires careful examination of the flare chromosphere, since this is the primary radiating source in flares. The majority of radiated flare energy emerges in the form of optical/UV lines and continua, but we are also now using the diagnostic information present in EUV continua and EUV emission lines formed at several million Kelvin in the upper flare chromosphere. All of the radiation is believed to be the 'reprocessed' kinetic energy of electrons accelerated during flares, and provides diagnostics for physical properties of the plasma in which energy is being deposed and dissipated. The chromosphere is also the location of hard X-ray 'footpoint' sources – the bremsstrahlung emission that is the diagnostic for the non-thermal electrons believed to be a major carrier of energy during a flare, and is thus a major clue to the fundamental process of flare energisation.

Timeliness

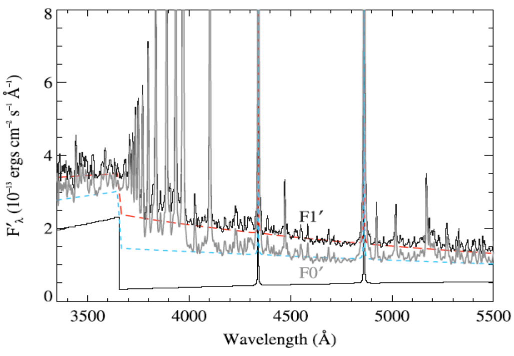
Since the last ISSI team proposal in 2009 there have been several key developments led by existing and new members of the proposed team, which have prompted us to request a rapid follow-up, to investigate the implications of these developments, and take advantage of the possibility of targeted observations with multiple instruments during the next couple of years of solar maximum. These developments include (1) new EUV spectroscopic line diagnostics of the conditions in the upper chromosphere during a flare [9, 14, 15]; (2) new observations of the flare continuum emission in both solar and stellar flares [12, 13, 16, 17]; (3) new techniques developed to probe the spatial structure of flare non-thermal electron emission [2, 11]. The upcoming launch of the IRIS spacecraft is also an excellent reason for convening the team.

Key questions:

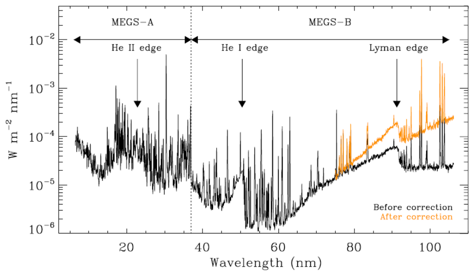
The key questions of solar chromospheric flares are how to use the observations to build up a picture of the structure and evolution of thermal and non-thermal plasmas in a flare, and how to combine this with flare modeling to understand flare energy deposition in the chromosphere during the impulsive phase. This is a complex and long-standing problem, but even within the last 3-5 years, observational and theoretical techniques have improved substantially, and some unexpected observations have been made. With these developments in mind, we expand below on the scientific motivation, the ideas, and the approach to be taken by the team.

<u>Flare continuum emission:</u>

Analysis and modeling of solar and stellar flare continuum emission will be emphasised [1, 4, 10] Flare continuum corresponds to heating and ionisation of the mid- to low-chromosphere resulting in optically thin free-bound continuum radiation, and/or an increase in the temperature of the optically thick atmosphere leading to an enhanced blackbody component [7]. We have new, detailed observational evidence for both types of emission in solar and stellar flares. Solar flare optical spectra are very poorly sampled, but imaging and



Above: Stellar flare spectrum at two times, showing also multi-component continuum fits (red,blue) including free-bound and a hot (10,000K) blackbody [12] the limited spectral information are sometimes consistent with optically thin continuum [16], and sometimes with a blackbody enhancement [17]. The exceptional detail (0.2", 30fps) available from ROSA (Rapid Oscillations in the Solar Atmosphere), and IBIS (Interferometric BIdirectional Spectrometer) instruments, which can be tuned to the flare continuum, can provide information on the rapid spatial and temporal variations necessary to distinguish between different heat input models, and we will plan observations with these.

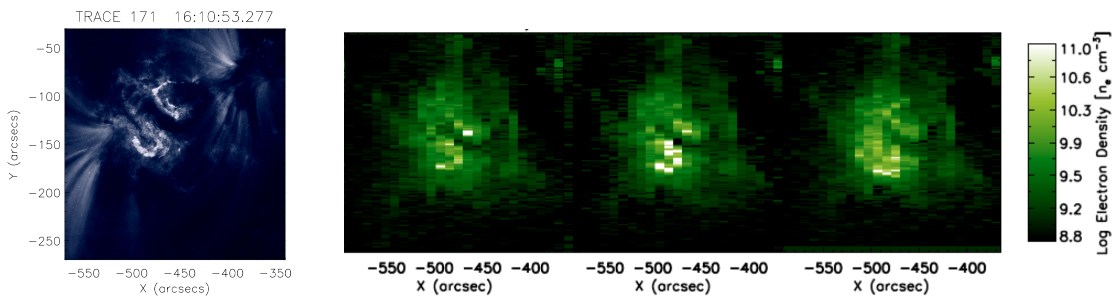


Above: EUV flare continuum spectrum from SDO/EVE (Milligan et al. 2012) showing several important flare continua and edges.

EUV hydrogen and helium continua have been well observed in a number of flares [e.g. 15] using the Solar Dynamics Observatory Extreme UV Variability Experiment (SDO/EVE), and can be complemented by high-resolution imaging, and detailed observations of hydrogen lines using the Multichannel Subtractive Double Pass Spectrograph (MDSP). In stellar flares the blackbody and continuum components dominate at different times [12]. Both stellar and solar optical observations also show properties, such as source height in the atmosphere, and the presence of hot blackbody components, that are not readily explained by existing simulations of electron beam heating of the flare atmosphere [12, 13]. There are suggestions also from the analysis of chromospheric hard X-ray sources – closely correlated with optical continuum emission – that HXR source vertical thicknesses are inconsistent with simple predictions from this model [2, 3], possibly requiring fine structure in vertical threads (2D modeling techniques for such configurations in solar prominences have been developed [5]). A concerted simulation effort, covering a broad range of electron beam parameters, as well as other possible heating models (waves, conduction), is a priority.

<u>Footpoint temperature and density structure:</u>

From the Extreme UV Imaging Spectrometer (EIS) on *Hinode* we have new spectroscopic diagnostics for the hot plasmas in the upper chromosphere of flares. These are being used by us to obtain detailed information on density, temperature, non-thermal velocity and emission measure. We will use this information to deduce the vertical structure of the heated upper chromosphere, which can be directly compared to simulation results. One of the more puzzling results arising from work by the last ISSI team was simply the large amount of plasma at high temperatures (up to 10 MK), and at chromospheric densities (up to 10^{11}cm^{-3}) present in chromospheric footpoints during the impulsive phase [9,14]. This is not expected from existing simulations of electron-beam heated atmospheres, which predict hot plasma in the corona but not the chromosphere. We will investigate how existing simulations can be reconciled with observations, and also how the available EUV data can be used to construct empiricals model of these regions.



Above: RH panels show density images of 1.5 MK plasma in the chromospheric footpoints of a small solar flare (LH panel) at three points during its impulsive phase. Hot, dense plasma is present in large amounts [9]

<u>Flare modeling</u>

One of the new members of our team is responsible for the best available flare radiation hydrodynamics model published so far [1]. As mentioned above, several new observations appear to stand in contradiction to the results of this model, which is based on energisation by electron beams albeit with parameters corresponding to one particular flare. It is therefore necessary to thoroughly explore the available parameter space for electron beam models including spectrum, minimum beam energy, and duration of injection pulses, and to generate model predictions for the newly observed lines and continua. The consequences of beam or wave-driven models of flare energy input will also be tested by adapting the simulations for energy input profiles having different parametric dependences on the flare atmospheric properties (such as temperature, plasma beta, or ionisation fraction). In a flare, non-LTE and non-equilibrium processes must be considered, and our team includes experts also in these areas. The flare models can also be used to deduce the observable parameters expected to be most sensitive to the flare atmospheric properties, informing planning for new observations.

Preparation for new instruments and missions

The team will provide modeling input for future generations of ground- and space-based instruments, particularly those with a strong chromospheric emphasis. We look forward to the launch in late 2012 of the interface Region Imaging Spectrograph (IRIS), which will open up the UV part of the spectrum for flare studies, for the first time in more than 30 years. Team member Carlsson is a Co-I on IRIS. We will investigate the possible flare diagnostics available in the IRIS wavelength range, and provide input to the IRIS team on optimal flare observations. In the more distant future, the next planned Japanese solar mission, Solar-C, is intended to carry a visible light imager, and high throughput UV/EUV spectrometers. New ground-based instrumentation awaits the arrival of the US Advanced Technology Solar Telescope (ATST, with planned first light around 2018), but in the meantime other team members will lead efforts to design and exploit the existing ground-based instruments IBIS, ROSA and MDSP, developing flare-observing strategies for future large facilities.

Brief Statement of Team's Goals

1. Use all available spectroscopic and imaging information to build an observational picture of the vertical structuring in temperature, density and ionisation, of flare chromospheric plasma in the impulsive phase.

2. Critically test the electron beam model of flare heating against the new observations, using a wider range of beam input parameters than in past simulations, and investigate the consequences of new flare energy input models.

3. Informed by present and historical observations, and the output of flare modeling, develop and use new UV flare chromospheric diagnostics for the IRIS spacecraft, and the future Solar-C spectrometers.

Team Membership

The solar chromosphere requires detailed modeling. We have firm commitments to participate from experts in radiative MHD with codes to model line and continuum spectra (Allred, Kowalski, Hawley) and perform detailed line and continuum calculations, including the non-LTE and non-equilibrium processes which are critical for the flare environment (Carlsson, Heinzel, Berlicki). Our team also covers a broad range of observational techniques, in ground based optical spectroscopy (Berlicki, Carlsson, Cauzzi, Hawley, Kowalski), X-rays (Battaglia, Fletcher, Milligan), UV/EUV spectroscopy (Heinzel, Milligan, Hudson), and imaging (Battaglia, Fletcher, Hudson, Milligan). The spectral coverage of stellar flares in the optical is better than that available for the Sun, so modeling and observation expertise (Hawley, Kowalski) in this closely related field is critical. The dialogue between solar and stellar flare physicists that occurred during the last team has already proved to be extremely profitable [8,12]

Four members of the previous team will not participate this time, and we have added new members to ensure that relevant expertise is available. Battaglia has been instrumental in developing powerful techniques to quantify the spatial characteristics of hard X-ray sources, and Allred is expert on radiation hydrodynamics modeling, having made the first detailed predictions of flare emission in the UV and optical, based on observed beam input parameters. Kowalski, previously a young scientist member, is now a full team member. We will invite two new young scientists. The full team list is below:

Lyndsay Fletcher (UK, *Team Leader*), **Joel Allred** (US), **Marina Battaglia** (Switzerland), **Arkadiusz Berlicki** (Poland), **Mats Carlsson** (Norway), **Gianna Cauzzi** (Italy), **Petr Heinzel** (Czech Republic), **Hugh Hudson** (US), **Suzanne Hawley** (US), **Adam Kowalski** (US), **Ryan Milligan** (UK)

Expected scientific advances and output

We will use sophisticated numerical simulations and high resolution observations address in detail the nature and location of solar flare energy input in the chromosphere, and in so doing constrain the physics of flare energisation. We will critically test the standard electron beam model of a flare, deciding whether or not it can be made consistent with the multitude of flare chromosphere observations. We will develop new flare diagnostics for the next generation of solar instrumentation. The results of our work will be made available in refereed publications and/or technical reports. We will continue to highlight to the community the scientific importance of chromospheric flare observations.

Programme, Facilities and Financial Support.

This project will comprise three stages, having some overlap: (1) review of recent observational results, literature investigation of possible UV diagnostics in the IRIS range, and planning of a scheme of simulations; (2) report on electron beam simulations and their match to observations, development of multi-instrument flare observing campaign with IRIS and, if necessary, new simulation runs; (3) report on new simulation runs, analysis of flare observing campaign(s). We therefore request three meetings of four days duration each, taking place in November 2012, April 2013, and November 2013. We will require standard ISSI facilities - a room with a data projector and internet access. We request support for the living expenses for the 11 named team members and 2 young scientists, for a total of 156 person-days, and travel support for the Team Leader and the young scientists.

Added value of ISSI support

The solar community now has a renewed interest in the flare chromosphere, just as observational, modeling, and theoretical capabilities have reached sufficiently high levels to tackle some of the hard problems. This community is spread worldwide, and so it is highly appropriate to have an ISSI venue for encouraging this research direction.

NASA has recently solicited, through its Living With A Star program, a topical theme on this subject, and we expect that several US-based proposals will be accepted in response to this solicitation. The ISSI activity will provide an independent and strictly international counterpart to the NASA-sponsored efforts.

Compatibility with ISSI aims

In accordance with mission of ISSI the goals of this team blend theory and observational data analysis, in an agenda that also looks towards new developments in instrumentation. The team will combine observations from ground and space-based instruments, since the primary chromospheric flare diagnostics span the infra-red to the X-ray. Finally, the object of study, the Sun and its activity, falls clearly within the scientific remit of ISSI.

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