Solar Chromospheric Flares

A proposal for an ISSI International Team

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Summary

Solar flares are the most energetic energy release events in the solar system. The majority of energy radiated from a flare is produced in the solar chromosphere, the dynamic interface between the Sun's photosphere and corona. Despite solar flare radiation having been known for decades to be principally chromospheric in origin, the attention of the community has recently been strongly focused on the corona. Progress in understanding chromospheric flare physics and the diagnostic potential of chromospheric observations has stagnated accordingly. But simultaneously, motivated by the available chromospheric observations, the 'standard flare model', of energy transport by an electron beam from the corona, is coming under scrutiny. With this team we propose to return to the chromosphere for basic understanding. The present confluence of high quality chromospheric flare observations and sophisticated numerical simulation techniques, as well as the prospect of a new generation of missions and telescopes focused on the chromosphere, makes it an excellent time for this endeavour.

The international team of experts in the theory and observation of solar chromospheric flares will focus on the question of energy deposition in solar flares. How can multi-wavelength, high spatial, spectral and temporal resolution observations of the flare chromosphere from space- and ground-based observatories be interpreted in the context of detailed modeling of flare radiative transfer and hydrodynamics? With these tools we can pin down the depth in the chromosphere at which flare energy is deposited, its time evolution and the response of the chromosphere to this dramatic event. We will undertake a program of advanced numerical simulation and multi-wavelength data analysis, and study the diagnostic potential that these bring, with the possibilities offered by future instrumentation in also mind.

Introduction and Overview

Solar flares are epochs of sudden and dramatic energy release in the solar atmosphere. The first recorded observation of a solar flare, 150 years ago in September 1859, 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.

Observations at EUV-X-ray wavelengths have since revealed the critical role of the solar corona in storing the pre-flare energy, but it is not possible to understand solar flares without studying the chromosphere. The chromosphere is the primary radiating source in flares, with the majority of flare energy emerging in the form of optical/UV lines and continua. This radiation is believed to be the 'reprocessed' kinetic energy of electrons (and possibly ions) accelerated during flares, and provides diagnostics for the energy deposition. The chromosphere is the location of hard X-ray 'footpoint' sources – the bremsstrahlung emission that is the diagnostic for non-thermal electrons, and thus a major clue to the fundamental process of flare energisation. The chromosphere is also understood to be the source of the hot, dense plasma that causes the dramatic brightening in coronal flare loops.

Research into the detailed physics of the flare chromosphere and the diagnostic potential of chromospheric radiation was very active during the 1980s, but since the arrival in the 1990s of the major space-borne coronal telescopes, the chromosphere has been somewhat overlooked. This does not mean that any of the problems of the flaring chromosphere have been solved. Rather, recent observations throw into question some of our long-held beliefs about the flare process, and the next generation of instruments promises chromospheric observations as a focus of attention. Meanwhile, the numerical techniques are now at the level of sophistication necessary to model the complexity of this most challenging layer of the Sun's atmosphere. It is with these facts in mind that we propose to return to the chromosphere.

Key questions:

In this Team we will revisit the key questions of chromospheric flares in the light of recent observational and theoretical advances

- How and where in the highly structured flare chromosphere are the most energetic flare emissions generated?
- How can the parameters of flare heating and electron acceleration be constrained using multi-wavelength observations and advanced numerical simulations?
- How can the very small spatial scales and fast temporal variations of chromospheric flare emission be understood in the context of flare heating models?
- Are observed chromospheric dynamics consistent with modeling?
- What are the most promising future chromospheric diagnostics for flare energetics?

Scientific Value

The conversion of magnetic energy into the kinetic energy of accelerated particles and plasma heating remains a major unsolved problem in solar physics, and in solar flare physics in particular. It is clear that in most flares the energy stored in the corona is radiated in the chromosphere, as established by current UV and white-light observations, and confirmed for the first time in the total solar irradiance (Woods et al., 2004). But how does that energy get to the chromosphere, how is it dissipated, and how can we use the huge, and relatively untapped multi-wavelength diagnostic potential of the chromosphere for both non-thermal and thermal processes? Below we mention a few recent striking developments in flare chromospheres and the questions that they stimulate, which will be addressed by the ISSI Team.

White light flares:
Previously thought to occur only in the most energetic solar flares, broadband 'white light' radiation has been found in small (low C-class) events (Hudson et al. 2006) and even one yet smaller B-class event (Jess et al., 2008). How is this radiation, thought to require the excitation of deep layers in the chromosphere, produced in such weak flares?

Compact footpoints:
New imaging in the UV to IR shows that flare chromospheric footpoints have a very small area (~10^{16} cm^2). This is particularly visible in the few flares seen by the Solar Optical Telescope on Hinode (e.g. Isobe et al. 2007). Small footpoint areas challenge models of flare energy transport by an electron beam from the corona, as the number of electrons per second per unit area approaches or exceeds that which can be stably supplied (Fletcher et al. 2007). This forces us to carefully re-examine the role of electrons in flare energy transport.

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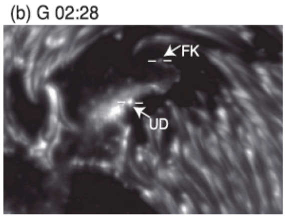


Image from Isobe et al. (2007) of the chromospheric footpoint (marked FK) of a major flare, with a FWHM of 500km

Hot footpoints:
EUV and soft X-ray imaging shows rapidly-varying brightenings (Hudson et al 1994, Fletcher & Hudson 2001) implying fast heating and cooling of the dense chromospheric plasma. How is this plasma heated to million-degree temperatures? Recent radiative MHD models of beam heating (e.g. Allred et al 2005, Abbett & Hawley 1999) are hard-pressed to deliver such rapid changes, as the hot plasma in such models is typically at coronal density and cannot cool rapidly. Observations using EIS and RHESSI (Milligan & Dennis 2009) also show that some hot material (up to 2 MK) is downflowing, in stark contrast to common 'evaporation' models.

Oscillating footpoints
Ground-based optical spectroscopy (e.g. Cauzzi 2008) has revealed rapid line-of-sight plasma oscillations in flare Hα and Ca lines. What causes this? Does it represent a pulsation of the energy source – a beam, or even an Alfvénic excitation (Fletcher & Hudson 2008)?

Hard X-Ray imaging and spectroscopy

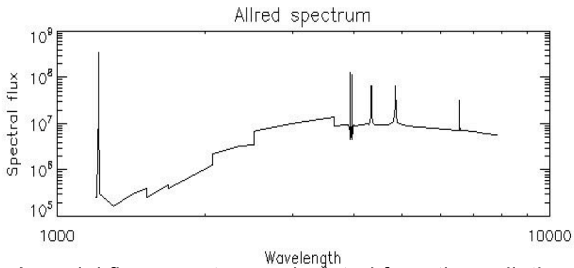
Hard X-rays are a critical diagnostic for non-thermal electrons in the chromosphere, and have been intensively studied with the RHESSI satellite. Imaging and spectroscopy of these sources with excellent spatial, spectral and temporal resolution is possible, placing strong constraints on the electron energy, spectrum and angular distribution. How do we best combine hard X-ray and optical diagnostics to study the depth dependence and rate of chromospheric energy input (e.g. Chen & Ding 2005), a strong test for the presence of a beam?

Advances in radiative transfer modeling

Strong chromospheric lines are formed under non-LTE conditions and can be influenced by non-thermal processes. Understanding the line formation is crucial for the correct interpretation of the line observations, and detailed modeling of non-LTE effects on the line shape and evolution is now carried out (e.g. Ding & Fang 2001, Berlicki 2007, Kasparova et al. 2007). Future, and even some present observations, (such as with the ROSA instrument on the Dunn Solar Telescope, and the CRISP instrument on the Swedish Solar Telescope) at very high frame rates can be used to study these non-equilibrium processes. Based on this modeling, what are the clearest line diagnostics, and what observations should we be making?

Advances in radiation hydrodynamic modeling

Another family of models are the radiative HD models, in which the evolution of the chromospheric plasma and radiation field are calculated, again in the non-LTE regime (e.g. (Abbett & Hawley, 1999; Allred et al. 2005). The effect of mass motion, heating, and density changes on the line profiles and on the broadband spectrum (see right), can be studied, for detailed comparison with observations (Milligan et al. 2006, 2009; Teriaca et al. 2006)



A model flare spectrum calculated from the radiation hydrodynamic simulations of Allred, Hawley, Abbett & Carlsson 2005)

Timeliness and Relationship to Ongoing International Activities

We see a new confluence of high-resolution observations and rapid progress in modeling capability. We have numerical simulations capable of simulating many aspects of the complex, coupled and rapidly evolving physics of the solar chromosphere, and we have the high spatial, spectral and temporal resolution observations necessary to constrain the flare chromosphere's physical parameters. Work in both areas must be extended and combined. It is furthermore a time of evolution in ideas about solar flares. Present-day observations e.g. of the isotropy of non-thermal electrons in the chromosphere (Kontar & Brown 2006) and the extreme beam fluxes required by very small flare chromospheric footpoints, (Fletcher & Hudson 2008) force us to look again at the usual 'coronal beam' model. Finally, there is the prospect of targeted chromospheric observations with a forthcoming series of solar satellites and major telescopes. This is therefore a propitious time for a 'return to the chromosphere', the most fundamental layer of the flaring atmosphere.

The major chromospheric space-based observatory at the present time is the diffraction-limited Solar Optical Telescope on Hinode. It has a spatial resolution of 0.2-0.3 arcseconds, sufficient to examine the intensity profile of flare chromospheric sources, and a high spectral resolution EUV imaging spectrometer which has already delivered new results on the mass motions of flare chromospheric plasmas. RHESSI observations place strong constraints on the total energy, spectrum, and even angular distribution of the electrons which play a central role in flare chromospheric excitation (Kontar & Brown, 2006). On the ground, a new generation of imaging instruments run at the extremely high frame rates necessary to capture the rapid evolution of chromospheric sources (for example IBIS on the Dunn Solar Telescope, CRISP on the Swedish Solar Telescope, and the Robotic Telescope in Ondrejov). We note that all space-based data are public access, and we have team members who are able to provide us with ground-based data (Cauzzi, Carlsson, Kasparova).

In addition to exploiting existing data, the team will be able to provide modeling input for future generations of space-based instruments particularly those with a strong chromospheric emphasis (e.g. the Chinese-French 'SMESE' mission, the proposed US 'IRIS' mission and one of the options for the proposed Japanese Solar-C). On the ground, the major planned European Solar Telescope (EST) and the US Advanced Technology Solar Telescope (ATST) projects both aim at understanding the chromosphere and its magnetic fields from modeling and observations.

Beyond flares, there is a renewed interest in the chromosphere, prompted by the astonishing new high-resolution observations from the ground and from the Hinode spacecraft. This has led to extensive theoretical developments in the modeling of the chromosphere and its dynamics. However, so far the most advanced of the radiative MHD models (see Carlsson 2007, and references therein) have concentrated on the quiet Sun with only one or two publications dealing with the disturbed flare atmosphere (e.g., Abbett & Hawley 1999, Allred et al. 2005). We will be able to capitalise on these advances in our studies of the flare chromosphere.

Goals

1. Because interest in solar chromospheric flares is just starting to pick up again after some years of relative quiet the first goal is to survey the state of the field, both in observations and theory, and to disseminate the information effectively to the team.

2a. The second goal is to design a set of numerical experiments that can be carried out by modelers in the team to allow benchmarking of numerical techniques.
2b. In parallel with 2a, the observers will identify a small number of candidate flare events for detailed observational study and comparison with theoretical calculations.

3. The codes will be run with different forms of heating input, for example reflecting different times during a flare. The observers and data analysts will simulate the observables from these code outputs.

4. One or more candidate events identified in 2b will be analysed and modeled in detail.

5. We will investigate new line and continuum diagnostics for flare chromospheric heating models, to provide input for new instrument development.

Team Membership

The solar chromosphere requires detailed modeling. We have firm commitments to participate from experts in radiative MHD with codes to model broadband spectra (Abbett, Carlsson, Hawley) and perform detailed line calculations (Ding, Heinzel, Kasparova), as well as electron beam simulations (Fletcher). Our team also covers a broad range of observational techniques, in ground based optical/IR spectroscopy (Berlicki, Cauzzi), X-rays (Fletcher, Milligan), UV/EUV spectroscopy (Heinzel, Milligan), and imaging (Fletcher, Hudson, Milligan). The spectral coverage of chromospheric flares on stars other than the Sun is better than that available for the Sun, so modeling and observation expertise (Hawley) in this closely related field is critical. The UK team leader (Fletcher) has substantial experience of leading a team of this size, via the RHESSI workshop series. The full team is as follows:

Lyndsay Fletcher (UK Leader), **Jana Kasparova** (Czech Leader)

Bill Abbett (US), **Arkadiusz Berlicki** (Poland), **Mats Carlsson** (Norway), **Gianna Cauzzi** (Italy), **Mingde Ding** (China), **Petr Heinzel** (Czech Republic), **Hugh Hudson** (US), **Suzanne Hawley** (US), **Ryan Milligan** (UK/US);

Anticipated output and advances

We expect that this workshop will lead to a renewed vigour in the field of solar chromospheric flare physics. 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 energy input from the corona. We will critically test the standard electron beam model of a flare, and we will work on crafting new flare diagnostics for the next generation of solar instrumentation. The following is a list of the output we expect from this Team

- Review of state of observations and theory of solar chromospheric flares (suitable for publication as a refereed review)
- Identification of a small number of events for careful data analysis, modeling and joint publication.
- Input to observation planning for existing and proposed future instrumentation (e.g. a technical document critically assessing observing sequences).

Programme, Facilities and Financial Support.

This project will require an initial review and synthesis of theoretical and observational work before developing and carrying out a new programme, and so we request three meetings of one week's duration each, taking place in November 2009, April 2010, and November 2010 (though these can be adjusted by agreement). 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 team members, for a total of 165 person-days, and travel support for the Team Leaders.

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 optical. Finally, the object of study, the Sun and its activity, falls clearly within the scientific remit of ISSI. Major modeling and observing efforts are taking place in the US, in Europe and in China, and the focused ISSI team setting provides the ideal environment for this.

References

Abbett, W. P. & Hawley, S. L. 1999, ApJ, 521, 906
Allred, J. C., Hawley, S. L., Abbett, W. P. & Carlsson, M. 2005, ApJ, 630, 573
Berlicki, A., Heinzel, P., Schmieder, B. et al, 2005, A+A 430, 679.
Berlicki, A., 2007, in *The Physics of Chromospheric Plasmas,* ASP Conf. Series 368, 387
Carlsson, M. 2007, in *The Physics of Chromospheric Plasmas,* ASP Conf. Series 368, 49
Carrington, R. C., 1859, MNRAS, 20, 13
Cauzzi, G., 2008, http://sprg.ssl.berkeley.edu/RHESSI/napa2008/talks/TueII_Cauzzi.pdf
Chen, Q. R. and Ding, M. D., 2005, ApJ 537, 542
Ding, M.D.. Qiu, J., Wang, H. & Goode, P. R. 2001, ApJ, 552, 340
Ding, M.D. and Fang, C., MNRAS 326, 943
Fletcher, L. & Hudson, H. S., 2001, Solar Physics, 204, 69
Fletcher, L, Hannah, I. G., Hudson H. S. and Metcalf, T. R., 2007, Ap. J. 656, 1187
Fletcher, L., Hudson, H. S. 2008, Ap. J. 675, 1645.
Hudson, H. S. et al, 1994, ApJ, 422, 25
Hudson, H.S., Wolfson, C.J., and Metcalf, T.R. 2006, Solar Phys. 234, 79
Isobe, H., et al. 2007, Publ. Astron. Soc. Japan 59, S807
Jess, D. B., Mathioudakis, M., Crockett, P. J. et al, 2008, ApJ 668, L119.
Jess et al., 2009, Science, 323, 1528
Kasparova, J., Varady M., Karlicky, M. et al. 2007, in ASP. Conf. Series, 368, 441
Kasparova,J., Varady, M., Heinzel, P. et al. 2009, A&A (accepted)
Kontar, E.P., and Brown, J.C. 2006, ApJ, 653, L149
Milligan, R. O., Gallagher, P. T., Mathioudakis, M. et al., 2006, ApJ, 638, L117
Milligan, R. O., & Dennis, B. R. 2009, ApJ, Accepted.
Teriaca, L., Falchi, A., Falciani, R. et al. 2006, A&A 455, 1123
Teriaca, L et al., A&A, 455, 1123
Woods, T. N. et al, 2004 Geophysical Res. Letts., 3110802