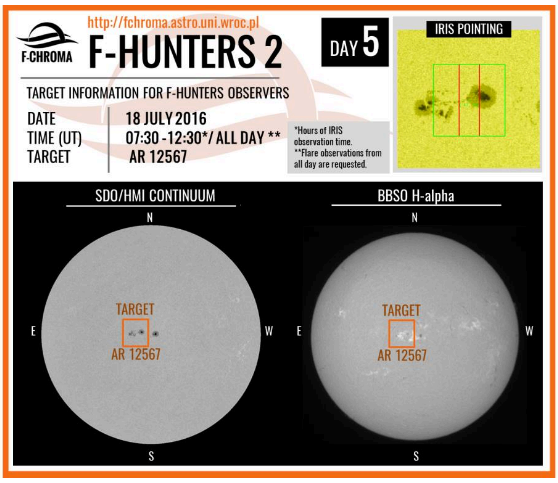
F-CHROMA Summary Report

1 Executive Summary

The F-CHROMA project was a dedicated multi-mode, multi-wavelength study of solar flares as observed in the lower solar atmosphere, or chromosphere. F-CHROMA scientists led numerous successful campaigns to observed flares from ground-based solar telescopes, co-ordinated with space-based facilities. This campaign data, and other data, consisting of flare images and spectroscopy, were analysed in combination with state-of-the-art numerical simulations to deduce the structure and evolution of the flare chromosphere, and understand the mechanisms by which energy is transported through the solar atmosphere in a flare, and dissipated in the form of heat, ionisation, and radiation.

Studies of the flare chromosphere enjoyed a renaissance with F-CHROMA, which succeeded in placing the importance of observing and understanding the lower-atmosphere energy input in flares front-and-centre for space missions such as IRIS, and the forthcoming major ground-based DKIST telescope. Our experiences in planning and executing flare observations have revealed optimal ways to obtain data on the all-important flare energy-release phase. Discoveries and advances from F-CHROMA included measurements of hot, fast upflows of hundreds of km/s from ‘elementary excitations’ in the chromosphere, each with an identical velocity profile. These are accompanied by cooler downflows of some tens of km/s, which appear to have an optically-thin component, leading to the exciting prospect of directly mapping the entire flow field in the chromosphere. F-CHROMA studies have demonstrated the critical role of hydrogen and helium ionisation in the temperature and dynamic structure of the chromosphere, and its central role in generating the broad-band UV, IR and ‘white light’ continuum emission by which flares were first identified. We showed areas of agreement and – perhaps more interestingly – disagreement with the 45-year-old ‘collisional thick target’ model of electron beam energy transport and deposition, and also made the first radiation hydrodynamic simulations of a flare atmosphere excited by a flux of Alfvén waves, showing that this is a viable alternative for generating flare heating and radiation. We have also embarked on the ambitious tasks of spectropolarimetry of the flare chromosphere, and on 2- and 3-D flare radiation transfer modelling; though at early stages they usefully point the way for future studies. And for the first time ever we have successfully cross-validated two independent flare radiation hydrodynamics codes, giving us confidence that – within the approximations of both codes – they are capturing the evolution of a flare atmosphere correctly.



Example target information disseminated daily to amateur observers as part of the F-HUNTERS pro-am campaigns

The F-CHROMA project produced an archive of the output of these flare models, which are tricky and time-consuming to run, along with the software necessary to interrogate and interpret the model output. An archive of high-quality ground-based flare observations has also been published, along with a catalogue of most ground-based flare observations in Cycles 23 and 24, and their space-based counterparts. We involved amateur astronomers in our flare observations, in two “F-HUNTERS” pro-am observing campaigns, with considerable success, and we disseminated the results of our project through more than 50 refereed papers, more than 100 presentations, and a training school for the next generation of solar flare physicists.

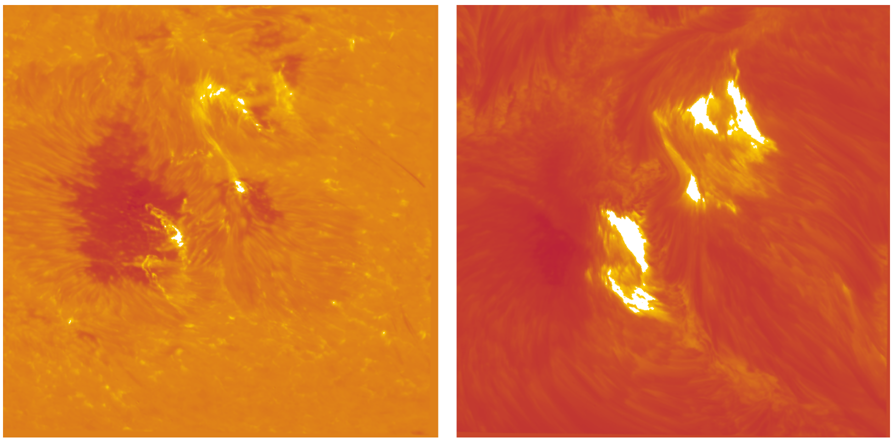
At the end of F-CHROMA, we have a vision of the flare atmosphere, and of flare energy transport, that emphasises excitation of the deep chromosphere, the central role of ionisation, and the great power of optically-thick radiation, such as will be observed in great detail by DKIST, to test different models of flare energy transport and solve long-standing puzzles in flare physics.

2 Project context and objectives

Our nearest star, the Sun, controls the solar system first and foremost by its gravitational presence and by the steady radiation output on which our existence on this planet relies completely. However, it also controls its environment in less obvious ways. The phenomenon of 'space weather' is increasingly in the public consciousness. Space weather encompasses many effects, but is primarily due to the influence of the Sun on the electromagnetic environment of the Earth, planets, and heliosphere. Sources of space weather are both solar flares, which are dramatic changes in the solar radiation at high energies in particular, and coronal mass ejections (CMEs) which are expulsions of magnetised, electrified gas (plasma) from the atmosphere of the Sun. The results of space weather at Earth are, primarily, disturbances in our magnetic field and heating of our upper atmosphere. Some decades ago this was of little relevance to human existence, but now our lives are highly dependent on, for example, spacecraft orbiting in that heated upper atmosphere and electrical power distribution systems that are sensitive to those magnetic disturbances. Therefore understanding the physical causes and effects of space weather, and working towards predicting its occurrence, is of central importance to our technological society.

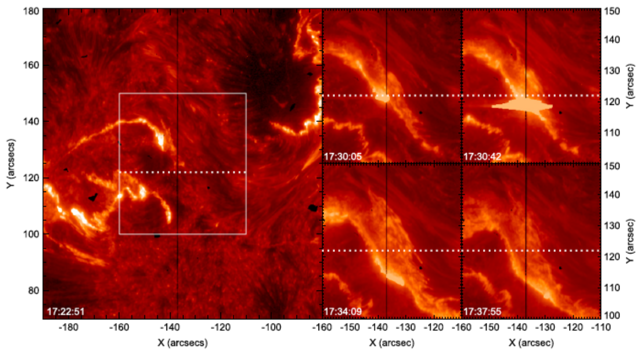
Solar flares are dramatic and short-lived flashes of radiation in the solar atmosphere. The total energy released in the form of flare radiation can be on the order of 10^{25}Joules, the energy equivalent to 2.5 billion megatons of TNT. This is provided by restructuring of stressed magnetic field in the outer atmosphere of the Sun (the corona) to a lower energy state. Solar flares are very often closely associated with CMEs, and the most intense radiation – which occurs in the optical and UV parts of the spectrum – is associated with, and likely caused by, substantial numbers of highly accelerated non-thermal particles. The centrally important question of flare physics is to understand how the energy stored in stressed coronal magnetic field is released so rapidly, transported through the atmosphere of the Sun, and converted – with very high efficiency – into the kinetic energy of the non-thermal particles and thus, or otherwise, into the flare's radiation output. This is a question that must be answered by putting together a broad range of observational and theoretical information. In the F-CHROMA project we focused on understanding how the transport and conversion of the flare energy can be deduced from observed flare radiation.

Solar flares were first observed in the optical in 1859 as rapid brightenings in white light from the solar surface, or photosphere. The development in the late 19th century of the spectroheliograph, which allows images to be made in isolated regions of the spectrum, revealed major disturbances in spectral lines now recognised to come from the narrow, complex interface between the photosphere and corona, the chromosphere. In particular, the 3-2 transition of hydrogen, Hα, characteristic of a plasma at ~10,000 K was extremely bright, and indeed analysis of this radiation is one of the main ways that we can understand what is happening in a flare. At that time flares were assumed to be entirely a chromospheric phenomenon, based solely on the energy implied by the enormous optical increases. However, with the associated sudden ionospheric disturbances detected by ground-based magnetometers, it became clear that flares involve substantial increases in ionising radiation at UV to X-ray wavelengths, verified by the dramatic, dynamical evolution of the coronal portion of the flare as seen from space in extreme UV and soft X-ray. Substantial advances in understanding of the magnetic and thermal evolution of flare plasma have been made by focusing on these energy ranges and on the coronal behaviour.



A solar flare seen during an F-CHROMA observing campaign in Hα off-band (left) and line centre (right). The image covers an area of 40,000 x 40,000km on the Sun. Images: P. Keys & D. Kuridze

Still, the solar chromosphere remains of primary interest during flares. It is here that the majority of the flare's radiative output originates, making it the main source of flare diagnostic information. Using chromospheric radiation we can deduce flare heating and ionisation, and subsequent cooling and de-excitation of different layers of the atmosphere. We can also measure plasma flows and non-thermal velocities, and infer character of accelerated particle distributions. The energy deposition and its variation in space and time can in principle be understood from the chromosphere and its observed evolution. However the chromosphere is a very complicated environment, so doing this successfully requires forward modeling – using first principles physical simulations to predict the radiation signatures arising from energy input in different forms. Novel developments in radiation hydrodynamical modeling address this problem, calculating the evolution of the chromospheric environment, and from this predicting the radiation signatures that allow a direct link from observables to physical conditions. Besides providing crucial flare diagnostics, the chromosphere may even be intimately related to the acceleration of the non-thermal electrons and ions that are a defining flare characteristic.



A solar flare on 10th September 2014 observed by the IRIS spacecraft. The black vertical line in the RH panels show where the spectrometer observed, giving information on hot, fast plasma flows accompanying the flare heating.

Our progress in this area has also been accelerated greatly by the acquisition of excellent datasets from both space-based and ground-based observatories. These facilities are observing at sub-arcsecond scales, corresponding to physical sizes on the Sun of 500km or less. This level of detail is probably still insufficient to capture the elementary *processes* happening on the Sun, but we do begin to have hints that important structures in space and time are not too far below our current capabilities. The flaring chromosphere emits across the entire electromagnetic spectrum, with different wavelengths characteristic of different temperature and locations (or heights, in a one-dimensional model) so that combining radiation signatures across wavelengths allows us, painstakingly, to build up a complete picture of its structure. No less important, but more difficult to interpret, is the information about the magnetic field in a solar flare, at the level of the photosphere and chromosphere, which can be deduced from the emitted radiation. We are just at the beginning of measuring and interpreting this emission.

The Sun is not the only star that produces flares. Indeed it seems to be a rather inactive star compared to many others of its own and other spectral classes (colour). However, it is the only star where we can directly image the flare and hope to understand how it works. By doing so, we may also extrapolate and apply our knowledge to other stars. Stellar flares have become a subject of great interest in the last few years as it becomes clear first of all how many stars have planetary systems around them, and secondly what the influences of the short wavelength radiation emitted during flares are both for the creation and destruction of conditions favourable to the production of pre-biotic molecules.

Following a long gap during which studies of the flaring corona were predominant, the central importance of the chromosphere in the energetics and dynamics of a flare (and the Sun as a whole) is being reasserted. Our project has capitalized on the renewed interest and investment worldwide in this fascinating region, leading to a multi-mode, multi-wavelength study of the solar flare chromosphere, supported by dedicated theoretical modeling. This concerted international effort in joint science exploitation of space-based and ground-based data, theory and numerical simulation has led to significant advances in our understanding of the physics of solar flares, and a roadmap for further developing this in the future.

F-CHROMA

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