Summary

Solar flares are sudden, explosive releases of the magnetic energy stored in the Sun. They often affect a wide range of solar regions: the corona, the chromosphere, and the photosphere, influencing their temperatures, densities, and magnetic fields. Space weather and thus its influence on the Earth is largely driven by flares, but their prediction and detailed mechanisms throughout the solar atmosphere are still unclear. The overall goal of this project was to understand the connections and interplay of different solar layers during flares. We investigated the flare mechanisms with state-of- the-art methods by combining data from RHESSI, IBIS, Hinode, IRIS, and SDO. The combination of these data allowed us to study the three-dimensional structure of the solar magnetic and we discovered changes of the chromospheric magnetic field during a flare. Such multi-instrument studies have rarely been attempted in the past because these different telescopes and spacecraft, observing methods, and analysis techniques require the combined expertise of different fields of heliophysics. The work resulted in more than 25 publications in refereed journals.

Work performed

- We obtained an unprecedented data set of an X-flare during a coordinated observing campaign, which have resulted in 11 related publications so far (4 were promised as deliverables, we greatly exceeded the goal)
- In collaboration with NASA, we released a press release and held a press conference about the “best-observed” solar flare
- We wrote observing proposals and were awarded time for service mode observations at the Dunn Solar Telescope in New Mexico USA and at the GREGOR telescope on Tenerife, Spain
- I published more than 25 papers, and was invited for 8 talks at international conferences
- I acted as the Flight Software manager for STIX/Solar Orbiter

Research Objective 1 (Magnetic structure in particle acceleration sites) was mostly focused on in the publication "The Fast Filament Eruption Leading to the X-flare on 2014 March 29", ApJ 806, 9, 2015 by Kleint et al. For RO 2, we detected chromospheric magnetic field changes in a flare for the first time and a publication was submitted to the Astrophysical Journal at the end of the grant period. RO 3 (patterns in solar flares and flare precursors) was investigated and resulted in several publications (e.g. Lui, Heinzel, Kleint, Kasparova, SoPh 290, 2015; Kleint et al., ApJ 816, 88, 2016). For RO 4 (Preparations for the launch of STIX onboard Solar Orbiter) I served as the flight software manager and participated in and coordinated several meetings with partners.

Collaborations with partners (Stanford University, New Jersey Institute of Technology, High Altitude Observatory, Max-Planck-Institut fuer Sonnensystemforschung, Kiepenheuer Institut) were carried out throughout the project and common papers are published (list below) and in progress.

All items from year 1 and 2 of the Gantt chart from the original proposal (page 22) have been carried out, apart from observing in person at the telescope, which was modified to service mode observations, having the advantage of not requiring me to travel to New Mexico and to have more time to write publications.

Main Results

The effects of flares are best visible in the chromosphere, for example as bright emission ribbons. It is assumed that this is where the bulk of the energy from particle beams is deposited. I acquired unprecedented chromospheric polarimetric data during a flare and found stepwise changes of the line-of-sight magnetic field (Kleint 2016, submitted to ApJ, see Fig. 1). This indicates large forces acting on the lower solar atmosphere

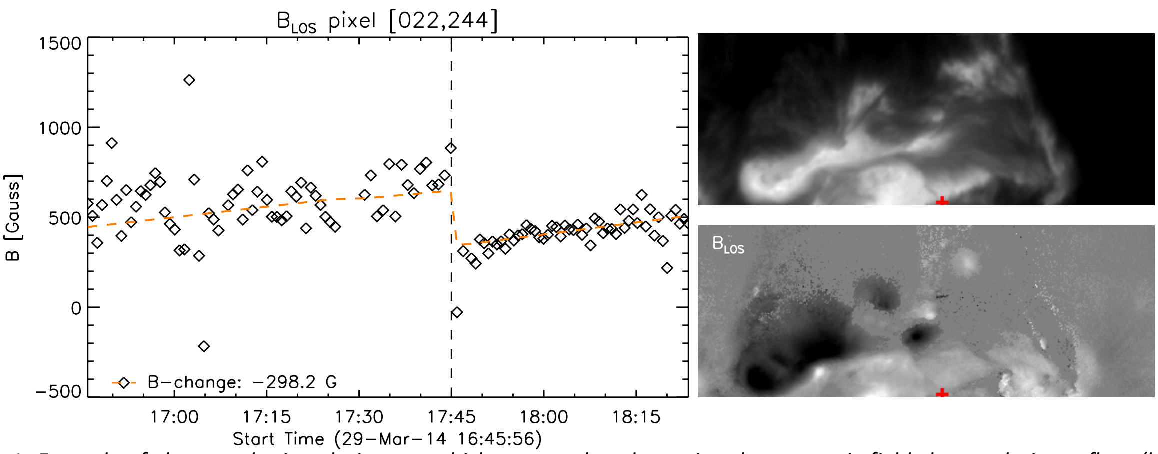

Fig. 1: Example of chromospheric polarimetry, which was used to determine the magnetic field change during a flare (left). The dashed vertical line denotes the flare onset time, the fit to the data series is shown in orange and a step of ~-300 G was observed. Right: Location of the selected pixel (red cross) on a chromospheric intensity image (top) and a chromospheric magnetogram (bottom).

during flares, whose origins are yet unknown and an unexpected result was that changes in the photosphere and chromosphere do not seem to be connected, neither in time or space.

Another main result included determining the origin of continuum emission during an X-flare. Enhanced continuum emission is observed for many flares, yet there is no consensus on its atmospheric formation height. While accelerated electrons are most likely stopped in the chromosphere and deposit their energy in that layer, the photospheric continuum is often enhanced too. The so-called “backwarming”, which would transport energy from the chromosphere to the photosphere has been proposed as responsible mechanism. We combined multi-wavelength observations from RHESSI (X-ray), IRIS (UV), HMI (visible), and FIRS (IR) to investigate the spectral shape, the timing, locations and the energetics of continuum emission. We found that the continuum is emitted in both, chromosphere and photosphere, through different mechanisms (hydrogen recombination and H- emission). The timing of continuum emission is nearly immediate with a delay of no more than 15 s after HXR emission at a given location. The energy contained in most electrons >40 keV, or alternatively, of ~10-20% of electrons >20 keV is sufficient to explain the observed continuum emission.

Final results and their potential impact and use

Our final results are more than 25 publications, with more than hundred citations already. Our work is widely accepted and appreciated in the solar community, also visible through 8 invitations for talks at international conferences of the researcher.

The potential impact of our results includes advances in the understanding of flares and possibly steps closer to flare prediction by observing Doppler shifts in filaments in pre-flare phases.