Living with a Star Targeted Research and Technology

Flare Dynamics in the Lower Solar Atmosphere

Annual Team Progress Report

February 2013 to February 2014

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This is the first year of this LWS Focused Science Team (FST). Our collaborative efforts have been focused on the following three objectives: (1) understanding the transport of energy and momentum into the interior from the solar atmosphere during flares, (2) understanding high-energy phenomena in the impulsive phase of flares, especially the transport of high-energy particles from the corona in relation to the thick-target model, and (3) studying the changes of vector magnetic fields in the photosphere associated with flares. In this report, we summarize the progress in the aspects of organization of the team effort, identifying collaborative projects, highlights of scientific achievements, and the tasks for the year 2.

1. Organization of Team Effort

In the past year, we organized two team meetings. The first meeting was held at Stanford University on 2013 February 15, when each team reported their research status and presented their science goals. We discussed the strategy of formulating the team science plan, particularly in terms of the collaborative effort. We also discussed the issue of involvement and collaboration with the wider community.

The second meeting was held at Montana State University on 2013 July 12. Besides presenting the progress of each team, we mainly discussed two team efforts related to the observational inputs for modeling and comparison between modeling results and observations. The science plan was also finalized. Several active regions were selected as the team targets. The team will focus on the study of two flares in AR 11158, the M6.6 flare on 2011 February 13 and the X2.2 flare on 2011 February 15. The X2.2 flare is associated with a strong sunquake, while the seismic signature of the M6.6 flare is not clear. In addition, two other flares in AR 11283, including the X2.1 flare on 2011 September 6 and the X1.8 flare on 2011 September 7, were selected for further analysis. The latter weaker event produced a sunquake while the former stronger flare did not.

In the science plan that we have submitted to NASA , we described members of this FST, the topic of investigation of each proposal, a matrix demonstrating the expected collaborative research, a detailed plan for each of the above three objectives, and finally, the anticipated milestones.

2. Identifying Collaborative Projects

Allred and Petrosian groups have started the collaboration in implementing the warm target Coulomb collision in the model. Allred recently made the implementation for the particle transport code by including an effective coefficient in the Fokker-Planck equation. This transport code is from James McTiernan's dissertation work under Prof. Petrosian's supervision, which is basically the same module used in the current Stanford Flare code including both particle acceleration and transport. The Petrosian group has implemented in the acceleration module the warm target Coulomb collision that adds to both the diffusion and energy loss coefficients. A plan is to extend this more rigorous treatment to the transport module and compare the result with that of Allred. Allred will also provide his improved RADYN radiative transfer hydrodynamic code to Fatima Rubio da Costa, who is currently working on combining RADYN with the Stanford Flare code.

Wang and Allred teams have planned a model-observation comparison in the low atmosphere flare emissions. Besides the white-light emission, the collaboration is particularly towards the understanding of black-light flares discovered with He D3 (as recently clearly shown by Liu team) and 10830 lines. The 10830 line is already in Allred's code, while D3 will be added in the modeling. Yan Xu from Wang's team will visit Allred in Feb. 2014.

Kosovichev team started the collaboration with the Stanford team of Petrosian on the hydrodynamic thick-target models and their comparison with observational results from the HMI data.

Kleint and Petrosian initiated a collaborative study of an M3 flare on 2011 September 24. This flare was well observed by IBIS at NSO/Sac Peak (Kleint) in H-alpha and Ca lines, by RHESSI in X-rays, and likely by Fermi/GBM. A collaboration plan has been made. The Kleint group will focus on reducing and analyzing the IBIS data, together with SDO/AIA and HMI data. The Petrosian group will analyze RHESSI data to obtain the electron spectrum, the result of which will be fed as an input to the hybrid particle and radiative hydrodynamic simulation. Then they will numerically synthesize the H-alpha and Ca line emissions and make the comparison with the IBIS observations.

Wang, Liu, and Kosovichev teams will collaborate in identifying the sunquake sources, and understanding their connection with flare emissions and vector magnetic field evolution. As Kosovichev is now appointed as the Director of Big Bear Solar Observatory, the collaboration using the data from the 1.6 m New Solar Telescope (NST) will be particularly important. Liu team will provide products of photospheric as well as 3D coronal magnetic field evolution.

Kleint team has special expertise in analyzing NSO/IBIS flare data. Wang team has recently obtained IBIS observations of a number of flares. One of the days also had IRIS support. Kleint is a key player in the IRIS team. Therefore, the collaboration between Wang and Kleint teams will be critical in analyzing the data set.

3. Highlights of Scientific Achievements

3.1. Understanding the transport of energy and momentum into the interior from the solar atmosphere during flares

Kosovichev team is responsible for the detection and quantitative characterization of the helioseismic response using the time-distance diagram method and the holographic method. The initial results include an investigation of the relationship between the holography and time-distance methods for the sunquake study. It has been shown that due to the anisotropy of the sunquake wave fronts, the holography technique, which is based on the assumption that the wave propagation follows the theoretical quite-Sun model and is hence isotropic, does not give correct locations of seismic sources. To test these techniques and also to determine the location and height of the impact sources, we have performed numerical simulations using a 3D code of helioseismic wave propagation in the spherical geometry. Significant effort has been put in the creation of the sunquake catalog including all the M- and X-class flares.

In addition, Kosovichev (2014) has started a detailed investigation of the strongest sunquake event of the current solar cycle as observed by HMI during the 2012 October 23 X1.8 flare.

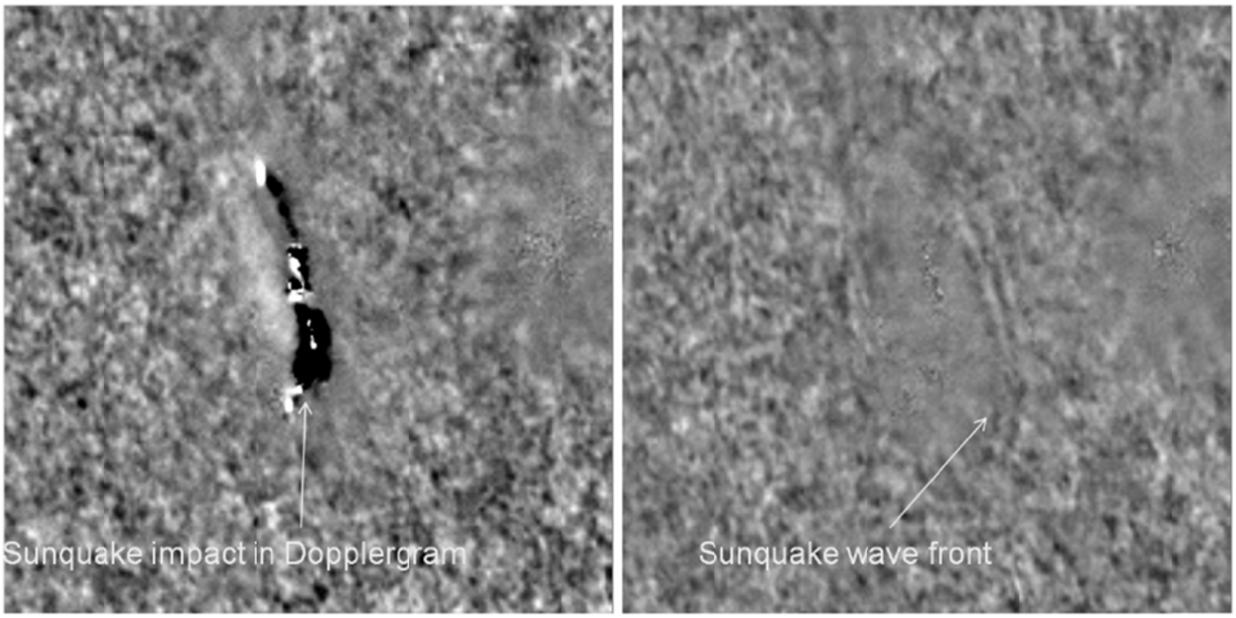

Figure 1: Left: The initial sunquake impact of the X1.8 flare observed with HMI Dopplergrams. Right: The sunquake wave front (Kosovichev et al. 2014).

In Wang's team, Xu et al. (2014) studied a pair of homologous flares on 2011 September 6 and 7 in AR 11283. They investigated the white-light emission of these X-class flares with SDO's seeing-free imaging spectroscopy. The results are similar in that both flares indicate analogous triggering and heating processes. However, the September 7 flare was associated with conspicuous sunquake signals, while there were no seismic waves detected during the earlier flare on September 6. Therefore, this comparison suggests that the particle bombardment may not play a determining role in creating sunquakes.

In the modeling side, Chen & Petrosian (2013) shows the ability to derive non-parametrically and directly the energy dependence of the escape time and energy diffusion coefficient from the count visibility data. These can then be converted to obtain the two basic characteristics of the wave-particle interaction, namely, the momentum and pitch angle diffusion coefficients.

3.2 Understanding high-energy phenomena in the impulsive phase of flares

Kleint team focused on studying a small flare observed by IBIS at NSO. It has complete spectral coverage in H-alpha and Ca II 8542 A lines. They found that Ca and H-alpha emissions follow each other closely, which indicates that the heating propagates quickly through the chromosphere. Sophisticated tools have been exclusively designed and developed for the spectro-polarimetric inversion of the IBIS data.

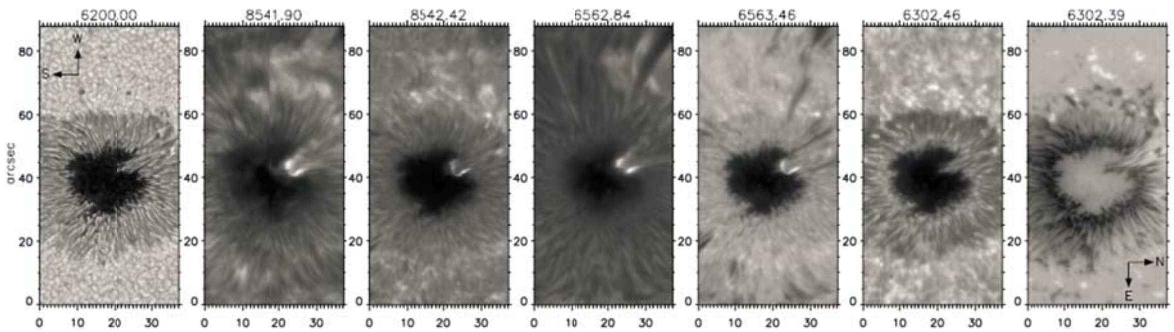

*Figure 2: A GOES-class B8.7 flare in October 2011 imaged with IBIS (*Kleint & Sainz Dalda 2014*).*

Petrosian team has focused on combining our Fokker-Planck particle acceleration and transport codes with the hydrodynamic RADYN code that includes detailed radiative transfer calculations. The RADYN code calculates the atmospheric conditions, which are turned into inputs for the team's particle acceleration code. The particle code then recalculates the heating rate along the loop and gives it to the RADYN code. The team has made substantial progress in combining the two codes. The team is in collaboration with Lucia Kleint to compare the shape, intensity, and temporal variation of the observed and calculated spectral lines.

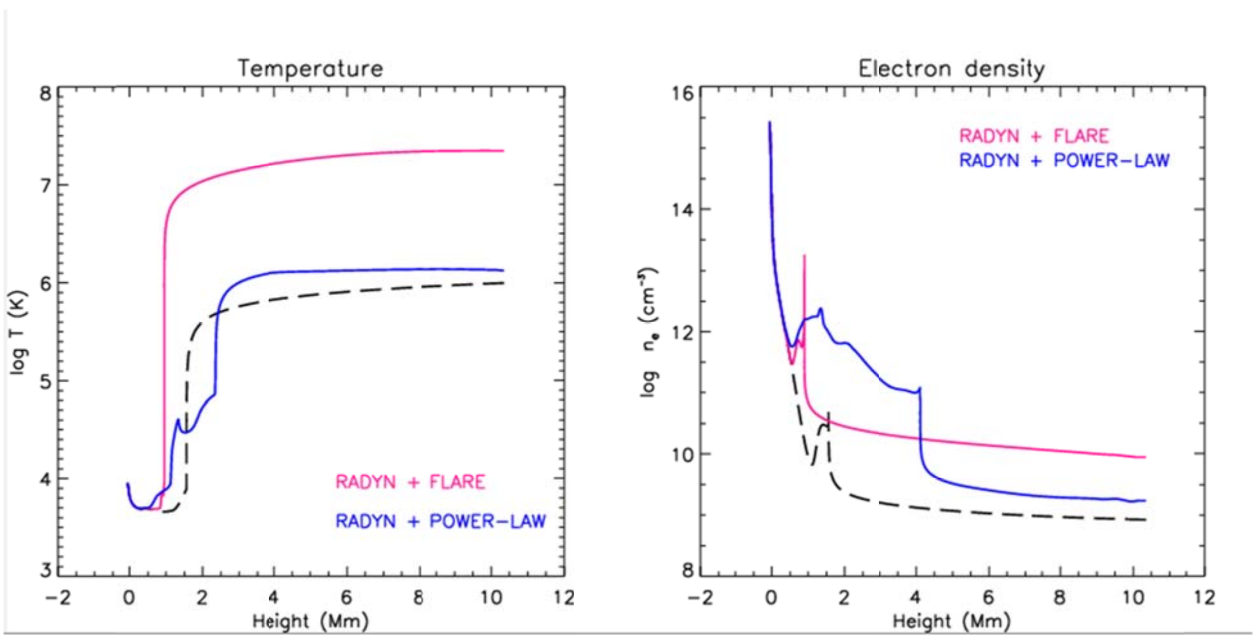

Figure 3: Distribution of the temperature [left] and electron density [right] along the flare loop at t=30 s when the flux of injected electrons reaches its maximum (Fpeak=8.6 erg/s/cm^2). Here we compare two cases of different injected electron spectra, a power-law (blue) and a quasi-thermal component plus a non-thermal tail given by our stochastic acceleration model (red). The dashed black line represents the escaping electron flux (Rubio da Costa et al., 2014, in preparation).

Liu et al. (2013) reported D3 observations of the M6.3 flare on 1984 May 22. The impulsive phase of the flare starts with a main elongated source that darkens in D3, inside of which bright emission kernels appear at the time of the initial small peak in hard X-rays. They suggest that this event resembles the so-called black-light flares that were proposed based on continuum images, and that D3 darkening and brightening features herein may be due to thermal conduction heating and the direct precipitation of high-energy electrons, respectively. This motivates the modeling of black-light flares especially in D3, which will be emphasized as a team effort.

Joel Allred has further used 1D radiative hydrodynamic code to model how the solar atmosphere responds to flare heating. Several input parameters were used considering the cut-off energy and power index, and white-light contrasts are derived.

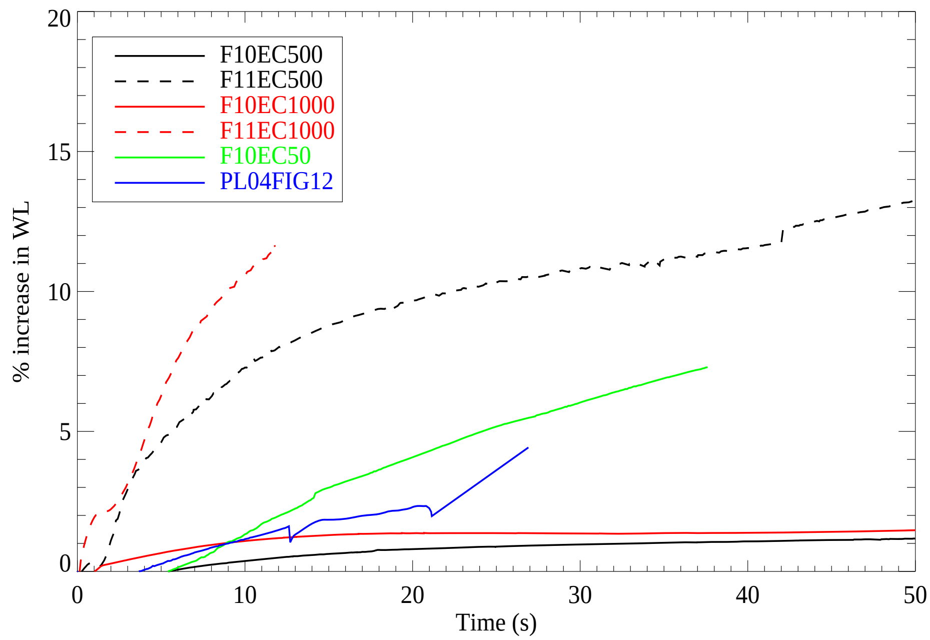

Figure 4: WL intensity as a function of time for several different input parameters using . 1D radiative hydrodynamic code.

3.3 Studying the changes of vector magnetic fields in the photosphere associated with flares

Rapid, irreversible changes of magnetic topology and sunspot structure associated with flares have been systematically observed in recent years but only with low-resolution (about 1") magnetograms and white-light images. Taking advantage of the 0.1" spatial resolution and 15 s temporal cadence of NST at BBSO, Wang et al. (2013) reported in detail the rapid formation of sunspot penumbra at the magnetic polarity inversion line (PIL) associated with the C7.4 flare on 2012 July 2. It is unambiguously shown that the solar granulation pattern evolves to an alternating dark and bright fibril structure, the typical pattern of penumbra. Interestingly, the appearance of such a penumbra creates a new Delta sunspot. The penumbral formation is also accompanied by the enhancement of the horizontal field observed using vector magnetograms from HMI. We explain our observations as being due to the eruption of a flux rope following magnetic cancellation at the PIL. Subsequently, the re-closed arcade fields are pushed down toward the surface to form the new penumbra. Nonlinear force-free field (NLFFF) extrapolation clearly shows both the flux rope close to the surface and the overlying fields.

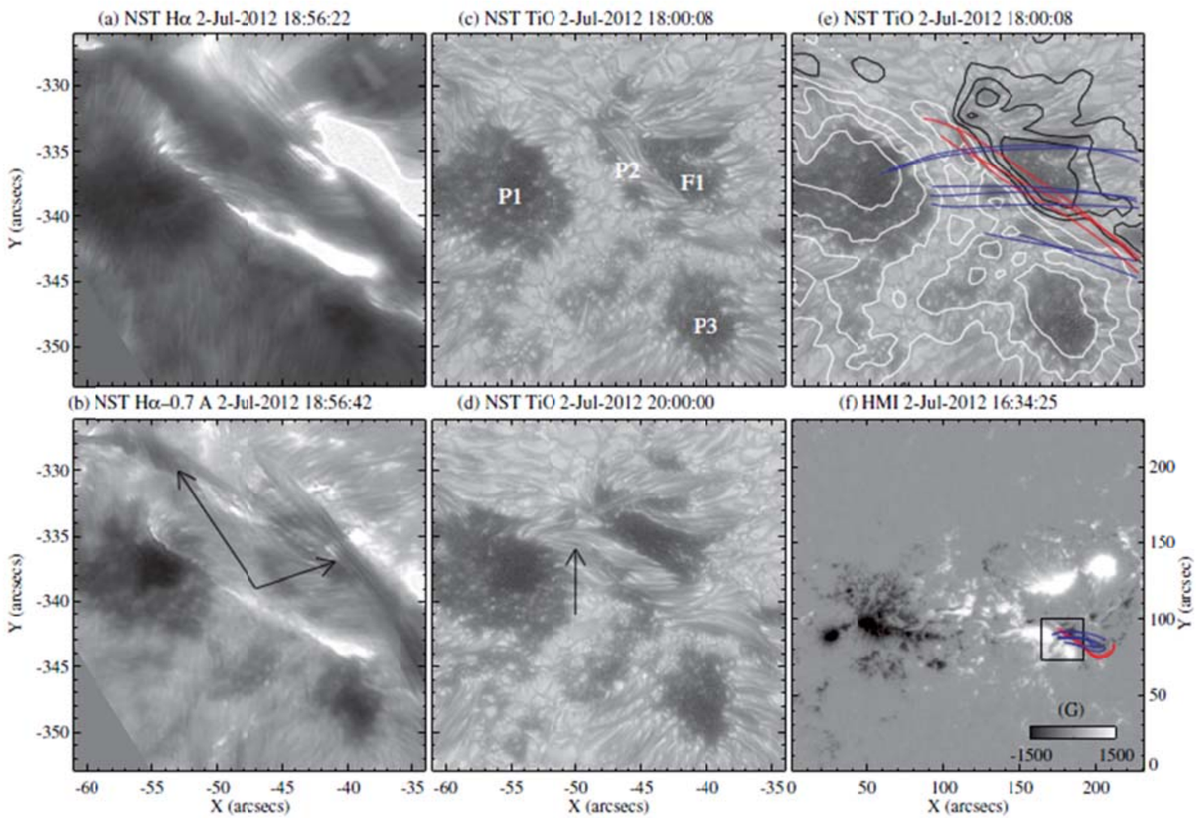

Figure 5: NST H-alpha center (a) and blue-wing (b) images at the flare peak time showing the two flare ribbons and the possible signature of flux rope eruption (pointed to by the arrows in (b)). The NST TiO images about one hour before (c) and one hour after (d) the flare clearly show the formation of penumbra (pointed to by the arrow in (d)), which connect the northern two umbrae lying in the opposite magnetic field (Wang et al. 2013).

Using an improved NLFFF extrapolation technique, Liu et al. (2013) presented a visualization of field line connectivity changes resulting from tether-cutting reconnection over about 30 minutes during the 2011 February 13 M6.6 flare in NOAA AR 11158. Evidence for the tether-cutting reconnection was first collected through multiwavelength observations and then by analysis of the field lines traced from positions of four conspicuous flare 1700 A footpoints observed at the event onset. Right before the flare, the four footpoints are located very close to the regions of local maxima of the magnetic twist index. In particular, the field lines from the inner two footpoints form two strongly twisted flux bundles (up to ~1.2 turns), which shear past each other and reach out close to the outer two footpoints, respectively. Immediately after the flare, the twist index of regions around the footpoints diminishes greatly and the above field lines become low-lying and less twisted (<=0.6 turns), overarched by loops linking the two flare ribbons formed later. About 10% of the flux (~3 x 10^{19} Mx) from the inner footpoints undergoes a footpoint exchange. This portion of flux originates from the edge regions of the inner footpoints that are brightened first.

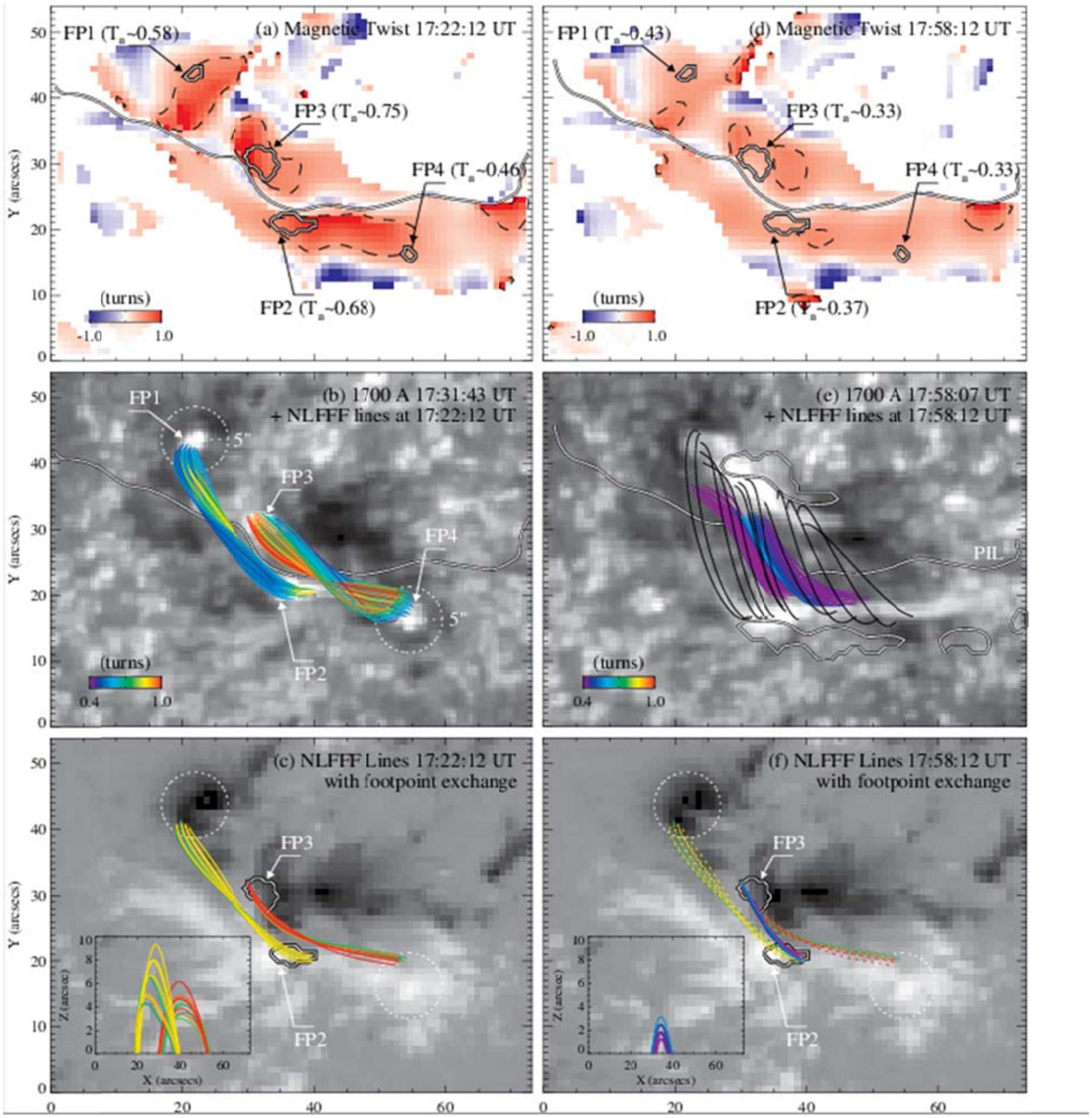

Figure 6: Results from Liu et al. (2013) for the 2013 February 13 M6.6 flare. (a) and (d): Tn (magnetic twist index) maps superimposed with dashed contours of 0.5 turns and white contours outlining the flare footpoints FP1–FP4. (b) and (e): NLFFF lines traced from FP2 and FP3 and colored according to Tn at their footpoints. In (e), the black lines connecting the ribbons are not color coded, and the contours depict the regions of negative Tn in (d). (c) and (f): Field lines exhibiting a footpoint exchange. The insets are the side view from the south.

4. Focus of Research in 2014

We have identified a number of events, as stated in previous sections, for further targeted research. The observational analysis and modeling work will be carried out for these events as the joint effort of this FST.

Observation and Data Analysis:

- Complete the initial sunquake catalog for all the M- and X-class flares observed by SDO/HMI.

- Investigate the statistical relationship between the sunquake sources detected by the time-distance and holography techniques. Investigate magnetic field and continuum emission variations in sunquake events, and also the relationship between these variations and high-energy flare emissions.

- Carry out spectro-polarimetric analysis of flares obtained with BBSO/NST and NSO/IBIS. Corresponding IRIS, microwave, and hard X-ray data will be jointly analyzed.

- Study the evolution of vector magnetic fields and velocity fields associated with flares. NLFFF extrapolation tools will be utilized to understand the 3D field restructuring.

Modeling:

- Continue exploration of the acceleration mechanism of electrons, and start to expand the acceleration-transport code to include the acceleration of protons. This will provide a more accurate heating rate and can be important for analysis of flares with strong gamma-ray emission indicating a substantial contribution from protons. The improved code will then be coupled with the combined electron/proton acceleration-RADYN codes. The feedback of the hydrodynamic response on the acceleration of these particles will be further investigated.

- Perform initial realistic 3D simulations of the atmospheric and helioseismic responses to solar flares.

- Include He D3 lines in the modeling towards a viable explanation of black-light flares.

Meetings:

Two team meetings are being planned for 2014. One in east coast and the other in west coast.

5. **Publications:**

Chen, Q. & Petrosian, V. 2013, *Determination of Stochastic Acceleration Model Characteristics in Solar Flares*, ApJ, 777, 33

Deng, N., Tritschler, A., Jing, J., Chen, X., Liu, C., Reardon, K., Denker, C., Xu, Y., & Wang, H. 2013, *High-cadence and High-resolution Hα Imaging Spectroscopy of a Circular Flare's Remote Ribbon with IBIS*, ApJ, 769, 112

Kleint, L. & Sainz Dalda, A. 2014, *The Evolution of Chromospheric Heating During the B8.7 Flare on Oct. 15, 2011*, in preparation

Kosovichev, A.G. 2013, *Sunquakes and Starquakes*, in "Precision Asteroseismology", Proc. IAU Symposium 301, Cambridge Univ. Press (in press)

Kosovichev, A.G. 2014, *Sunquakes: Helioseismic Response to Solar Flares*, in "Extraterrestrial Seismology", Cambridge Univ. Press (in preparation)

Liu, C., Deng N., Lee, J., Wiegelmann T., Moore, R.L., & Wang, H. 2013, *Evidence for Solar Tether-cutting Magnetic Reconnection from Coronal Field Extrapolations*, ApJL, 778, L36

Liu, C., Xu, Y., Deng, N., Lee, J., Zhang, J., Prasad Choudhary, D., & Wang, H. 2013, *He I D3 Observations of the 1984 May 22 M6.3 Solar Flare*, ApJ, 774, 60

Liu, W., Chen, Q., & Petrosian, V. 2013, *Plasmoid Ejections and Loop Contractions in an Eruptive M7.7 Solar Flare: Evidence of Particle Acceleration and Heating in Magnetic Reconnection Outflows*, ApJ, 767, 168

Wang, H., Liu, C., Wang, S., Deng, N., Xu, Y., Jing, J., & Cao, W. 2013, *Study of Rapid Formation of a δ Sunspot Associated with the 2012 July 2 C7.4 Flare Using High-resolution Observations of the New Solar Telescope*, ApJL, 774, 24

Xu, Y., Jing, J., Wang, S., & Wang, H. 2014, *Comparison of Emission Properties of Two Homologous Flares in AR 11283*, ApJ, submitted

In addition, a numerous presentations were made in the 2013 SPD and AGU meetings.