Living with a Star Targeted Research and Technology

Focus Team Science Plan

Flare Dynamics in the Lower Solar Atmosphere

June, 2013

Joel Allred (NASA GSFC)

Lucia Kleint (BAER Institute)

Alexander Kosovichev (Stanford University)

Chang Liu (New Jersey Institute of Technology)

Vahe Petrosian (Stanford University)

Haimin Wang (New Jersey Institute of Technology, Team Leader)

A. Introduction

Solar flares are impulsive eruptions that can be observed in the entire wavelength range of electromagnetic waves from radio to gamma rays, as the consequence of acceleration of electrons and ions, and heating of the plasma. Study of flare dynamics in the lower atmosphere is one of the most important components in the flare research. On the one hand, flares are often closely associated with coronal mass ejections (CMEs) in large scales, which carry energy and momentum towards the interplanetary space. Many CMEs are associated with geomagnetic storms. On the other hand, below the solar photosphere, the evolution of magnetic fields coupled with velocity fields may play a major role in triggering flares. The downward transport of energy and momentum may cause the sub-surface response to eruptions, such as sunquakes as recently observed. The state-of-the-art observations from Solar Dynamic Observatory (SDO), in conjunction with the operation of several other current space-based solar missions as well as ground-based facilities, are essential to observe flares in a comprehensive way, and therefore will help provide physical understanding of flares with the aid of modeling.

To follow the guideline of the NASA LWS program announcement for this focus team topic, our collaborative research will focus 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. (3) Studying the changes of vector magnetic fields in photosphere associated with flares. In this focus team science plan, we describe the members of this focus science team (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.

B. FST Members:

1. Computational and Observational Investigations into Flare Accelerated Particles
PI: Joel Allred (NASA/GSFC)
Co-I: Gordon Holman (NASA/GSFC)

2. Characterization of Sunquake Signature in Terms of Energy and Momentum and Their Relationship with the Flare Impulsive Phase
PI: Alexander Kosovichev (Stanford)
Co-I: Junwei Zhao (Stanford)

3. Bridging the Gap in Space from the Ground: Dynamics and Magnetic Fields of Flares in the Photospheric and in the Chromosphere
PI: Lucia Kleint (BAERI)
Co-Is: Alberto Sainz Dalda (Stanford), Rebecca Centeno Elliott (HAO/NCAR)
Collaborators: Phil Judge (HAO/NCAR), Lyndsay Fletcher (Uni Glasgow), Hector Socas-Navarro (IAC)

4. Exploring the Physical Relationship among Photospheric Magnetic Field Changes, Sunspot Motions and Sunquakes during Solar Eruptions
PI: Chang Liu (NJIT)
Co-Is: Na Deng (NJIT), Haimin Wang (NJIT), Alina Donea (Monash University)
Collaborators: Peter Schuck (NASA/GSFC), Yang Liu (Stanford)

5. Coupling of Particle Acceleration and Atmospheric Response Processes in Solar Flares: Combined Kinetic-fluid Modeling and Comparison with Multiwavelength Observations.
PI: Vahe Petrosian (Stanford)
Co-I: Wei Liu (Standford)
Post-doc: Fatima Rubio
Collaborators: John Mariska (George Mason), Tiago Pereira(University of Oslo), Bart De Pontieu (LMSAL)

6. Study of Flare Footpoint Emission Using Advanced Observing Tools
PI: Haimin Wang (NJIT, Team Leader)
Co-Is: Carsten Denker (AIP, Germany), Yan Xu (NJIT)
Collaborators: Dale Gary (NJIT), Jiong Qiu (Montana State)
Graduate Student: Natsuha Kuroda

C. Collaboration Matrix

Science Goals	GSFC (Allred)	BAERI (Kleint)	Stanford (Kosovichev)	NJIT (Liu)	Stanford (Petrosian)	NJIT (Wang)
1. Understanding the transport of energy and momentum into the interior from the solar atmosphere during flares	Momentum transfer due to electron and ion beams	Vector field changes as function of time	Observation and simulation of sunquakes	Track sunspot motion; track flows using DAVE4VM; link to properties of sunquakes	Modeling of pressure impulse	Hard X-ray and microwave imaging to compare with sunquake impact sites
2. Understanding high-energy phenomena in the impulsive phase of a flare; transport of high energy particles in coronal and the relation to the thick target model	Modeling of electron beam; Ion beam heating and chromospheric response; 511 keV line	Particle beam through linear polarization	MHD simulation of energy and momentum impact		Mechanism of particle acceleration, and coupling with chromospheric response from electrons and protons	Optical, hard X-ray, microwave observations of flare footpoints; understand elementary bursts and implosion; Emission mechanisms of WLFs and BLFs
3. Extensions of the photospheric field changes from the line-of-sight field to the full vector field		3D magnetic structure covering photosphere, chromosphere and corona, with advanced inversion codes	Process HMI data and select events	Observation of vector magnetic field changes associated with flares		

D. Detailed Science Plan

D.1 Understanding the transport of energy and momentum into the interior from the solar atmosphere during flares

The physical process of flares requires both conservation of momentum and energy. The beaming of particles from upper to lower atmosphere would carry significant amount of energy and momentum. The kinetic energy is converted to heating and radiation in various forms in the lower atmosphere, while the downward transport of momentum may cause some observed effects even into the photosphere and the solar interior , such as sunspot motion and sunquakes. The team will attack this problem from the following specific points.

(a) Properties of Sunquakes

Using the strong connection with the HMI team, Kosovichev et al. will steam-line the holography and time-distance analysis of M- and X-class flares observed by HMI (with some events by MDI) to improve the detection of sunquakes. They will create the database, which provides the detection and characterization (such as egression power, location, timing, speed, decay rate) of sunquakes. The candidate events will be selected by the team, for the collaborative support.

Using the list as described above, Liu et al. will analyze selected events in collaboration with Dr. Donea at Monash University using helioseismic holography. The results will be compared with Kosovichev et al. Liu et al. will also compare the sunquake characteristics with the observed sunspot motion. The lateral flows will be derived using the software packages DAVE and DAVE4VM, in collaboration with Dr. Peter Schuck.

(b) Context Magnetic and Particle Observations

The observations of the particle and magnetic environment around sunquakes are very important for the understanding of momentum and energy transport. The context observation for the events as described above will be analyzed.

Wang et al. will carry out imaging spectroscopy in hard X-ray (HXR) and microwave, and align the constructed images with sunquakes. The electron distribution in multiple footpoints will be provided as inputs for the modeling as described below. Ion distribution by gamma ray imaging will also be attempted with RHESSI.

The magnetic observation will be carried out by Liu et al. and Kleint et al. Both groups will look into the evolution of magnetic fields associated with flares and sunquakes. Liu et al. will emphasize on the analysis of Hinode and HMI data, while Kleint et al. will extend the study to include imaging spectropolarimetry using NSO/IBIS. IBIS has high resolution and sensitivity, although the Stokes inversion is somewhat challenging in the chromosphere, but well-studied in the photosphere. In both studies, the rapid changes of magnetic fields from before to after flares will be characterized. The change of Lorentz force will be analyzed. The more detailed study will be discussed in section D.3.

(c) Modeling

The case-specific modeling will be carried out by three teams from different angles. Allred et al. will use 1D hydrodynamics model to study the energy and momentum transport of beaming electrons and ions. A specific question is whether these beams create sufficient momentum and energy for sunquakes. Petrosian et al. will use a combined kinetic-particle and hydrodynamic simulation. Although this modeling will be discussed in more detail for the next topic, the unique feature is to derive the pressure impulse, which provides the duration of transport of energy and momentum into the surface. Finally, Kosovichev et al. will use MHD wave simulation to estimate potential momentum impact and characteristics of sunquakes. The modeling from these three aspects as well as observations will be inter-compared.

The key science questions to be addressed are:

1. For a typical sunquake, what is the energy and momentum involved?
2. Why some flares have associated sunquakes, while many others do not?
3. What causes sunquakes?
4. Is there a relationship among change of magnetic fields, lateral sunspot motions, and sunquakes?
5. Is the modeled pressure impulse observable?

D.2 Understanding high-energy phenomena in the impulsive phase of flares, especially the transport of high-energy particles from corona in relation to the thick-target model

The FST will carry out joint observation and modeling studies to find (1) the acceleration of energetic electrons and ions, and (2) the atmospheric response to the energy transport of accelerated electrons and ions.

(a) Observations

The team will first identify a few events that have comprehensive coverage in HXR, visible, EUV, and microwave wavelengths. The 2011 February 15 X2.1 flare will be our initial target event.

Wang et al. will carry out RHESSI HXR spectroscopy to identify both looptop and footpoint sources. Data from Nobeyama radio observatory will also be analyzed to further study the properties of accelerated electrons. These observations will provide input and constraints for the modeling as described below. As HXR and microwave have sub-second cadence, the properties of elementary bursts will be analyzed to understand the particle acceleration in sub-second time scales.

Kleint et al. and Wang et al. will coordinate the effort to obtain the best available optical flare observations. These include space data from Hinode and SDO, and ground-based observations such as BBSO 1.6 m NST and German 1.5 m GREGOR. Both Kleint et al. and Wang et al. have observed flares at NSO/SP using the continuum and spectroscopic (IBIS) facilities. Wang et al. will pay special attention to the white-light observations using 1.6 um, which is formed in the deepest observable layer (the opacity minimum). It is important to understand the energy dissipation into such a deep layer. Kleint et al. will pay special attention to the photospheric and chromospheric spectropolarimetry. Her team has unique expertise in the inversion of spectral lines. The study of linear polarization is a key in search for the impact polarization of the beaming electrons.

(b) Modeling

The observations described above would provide inputs and constraints for the modeling.

Allred et al. will apply 1D hydrodynamic model using Fokker-Planck kinetic theory (with a resolution < 100 m) to derive the flare heating from electrons and ion beams. Direct ionization can be caused by beam particles. With the assumption of optically thick non-LTE, over 25 atomic level populations can be derived. The modeled results can be compared with 10830 observations of Kleint et al., and visible and NIR continuum observations of Wang et al.

Recently we also pay attention to the so-called “black light flares”, which are most obviously observed in the He I D3 line. Allred et al. and Wang et al. will intend to compare the observation and modeling.

In addition, the modeling of ion beams is especially useful to explain the high temperature and density inferred from the 511 keV emission line. Joint effort of 511 keV observation and modeling will be carried out, to be led by Allred.

Petrosian et al.’s modeling will combine particle and hydrodynamic simulations. It is a nice complement to the effort of Allred et al. The new approach determines the details of the acceleration process from HXR observations. The new components of the simulation include pitch angle changes, magnetic field convergence, acceleration and transport of protons, and radiative transfer effect.

Kosovichev et al.’s effort will focus on nonlinear realistic 3D radiative MHD simulation of energy and momentum impacts on the lower atmosphere, including the thick-target model, localized heating, and magnetic field variation (see the next section). The simulation will be compared with characteristics of X-ray emissions and coronal dynamics.

The key science questions to be addressed based on the joint observational and modeling efforts on the specific chosen events are:

1. What are the mechanisms of electron and ion acceleration in flares?
2. How does the lower atmosphere respond to accelerated electrons and ion beams?
3. What causes white-light flares?
4. Can the black-light flares be observed and explained?
5. What are the physical mechanisms of sub-second elementary bursts?
6. What are the characteristics and physical interpretation of the 511 keV line emission?
7. How is the thick-target model related to the transport of high-energy particles from the corona?

D.3 Studying the changes of vector magnetic fields in photosphere associated with flares

The advanced observations from SDO/HMI and new modeling tools allow the team to systematically study the evolution of vector magnetic fields associated with solar flares. The changes in the photospheric field and the dynamics associated with flares/CMEs could serve as a direct observational probe of the energy transformations and momentum balance in the flare/CME process.

(a) Observations

Liu et al. will use vector magnetograms from SDO/HMI and Hinode supplemented by the archived and future data from BBSO to systematically study the temporal and spatial relationship between the changes of vector magnetic fields and the related dynamics, including signatures of flare energy re-lease, the CME launch, and variation of sunspot white-light (especially penumbra) structure. We will explore the connection of the properties of the Lorentz-force change with the flare magnitude and CME energetics. We will also trace the sunspot motions throughout the eruption process, and study the correlation between it and the horizontal component of the Lorentz-force change, in the directions both parallel and perpendicular to the flaring magnetic polarity inversion line. As related, the evolution of the sunspot rotational motion across the flare time will be characterized based on the flow field derived using the differential affine velocity estimator for vector magnetograms (DAVE4VM).

Besides analyzing SDO data, Kleint et al. will observe with IBIS and apply sophisticated spectral line inversion techniques to full-Stokes photospheric and chromospheric data. The goal is to investigate the 3D magnetic field configuration in the solar atmosphere necessary for the flare occurrence and its changes during and after flares. These efforts are complementary to those of Liu et al.

(b) Modeling

The modeling capability of the team for this topic is relatively limited. Kosovichev et al. will play a key role in using their 3D MHD modeling as described above to produce parameters that can be compared with observations, such as magnetic field and velocity variations associated with flares. We also seek collaboration with other modeling teams, especially those recently funded under the LWS program of NASA/NSF Partnership for Collaborative Space Weather Modeling.

The key science questions to be addressed are:

1. What are the systematic patterns of changes of surface magnetic fields and velocity fields associated with flares?
2. What are the signatures of chromospheric fields and their changes associated with flares?
3. Is there a relationship between change of fields and energy and momentum transport as described in the previous sections?
4. Can MHD modeling explain observed field changes?

E. Milestones

Year 1

The team will select commonly interested events. We will target 5 to 10 well observed events. The first event that the team already decided is the 2011 February 15 X2.1 flare, which has comprehensive data coverage. The data analyses and modeling tools will further developed. Science goals will be defined and fine-tuned. The first team meeting was held in February 2013, and the second team meeting is being planned for July 2013.

Year 2

In the two planned team meetings, results of observations will be discussed, and further joint observations and modeling efforts will be coordinated. Some understanding of sunquakes and changes of magnetic fields associated with flares will be achieved.

Year 3

The team will continue to carry out collaborative research on the selected flares, including archived and new events from all three angles: cause of sunquakes, high-energy particles, and magnetic field evolution. The acceleration model and MHD model will be matured for the comparison with observations.

We will prepare on-site review of the project.

Year 4

We will emphasize on the big-picture approach of the flare physics. Based on observational and modeling results of individual events analyzed by team members, we will propose a comprehensive understanding of the flare energy release, the surface/sub-surface response, and the associated evolution of magnetic fields.