

Probation Report

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1 Sunquakes

1.1 Introduction

During this age of space-born solar astronomy, understanding the highly dynamic environment of the Sun's atmosphere is a study enriched by a wealth of high detail observations. With each newly launched space instrument the spatial resolution of collected data increases, which coupled with those spacecraft that are tailored to capture light of previously unobserved wavelengths, often leads to new phenomena being observed. Eruptive solar flares fall into this category, in that spacecraft have provided observations that challenge the current theoretical view that the standard eruptive flare model (CSHKP model: (Carmichael, 1964; Sturrock, 1966; Hirayama, 1974; Kopp and Pneuman, 1976) puts forward.

Solar flares are one of the most energetic events to occur in the Sun's atmosphere, where by stored magnetic energy is released in the form of heat, mass motions, and accelerated particles. This highly dynamic process produces many measurable signatures, such as emission from γ -ray to optical wavelengths, a high percentage of which agree with the CSHKP model. However, this is not the full picture. The standard flare model has been modified to include new observations many times over the years (e.g., Shibata and Magara (2011)) and is still unable to describe some observed phenomena. Therefore there is still work to be done before a true account of the complex nature of solar flares can be realised.

Sunquakes are an observable feature during some solar flares that the standard model is unable to explain. It is believed that they are the result of energy and momentum released during the flare impacting the lower solar atmosphere. During a solar flare, energy is released high up in the solar atmosphere and transported down to lower altitudes. If a sufficient amount of momentum impacts the lowest atmospheric layer, then acoustic waves are produced which propagate into sub-surface layers of the Sun and are then observed on the solar surface as a sunquake (see Figure 1a). As acoustic wave-fronts travel into the interior they encounter layers of increasing density causing refraction back toward the solar surface (see Figure 1b). At which point, waves can be observed as circular formations in the surface plasma, expanding outward from a point of origin (see Figure 2).

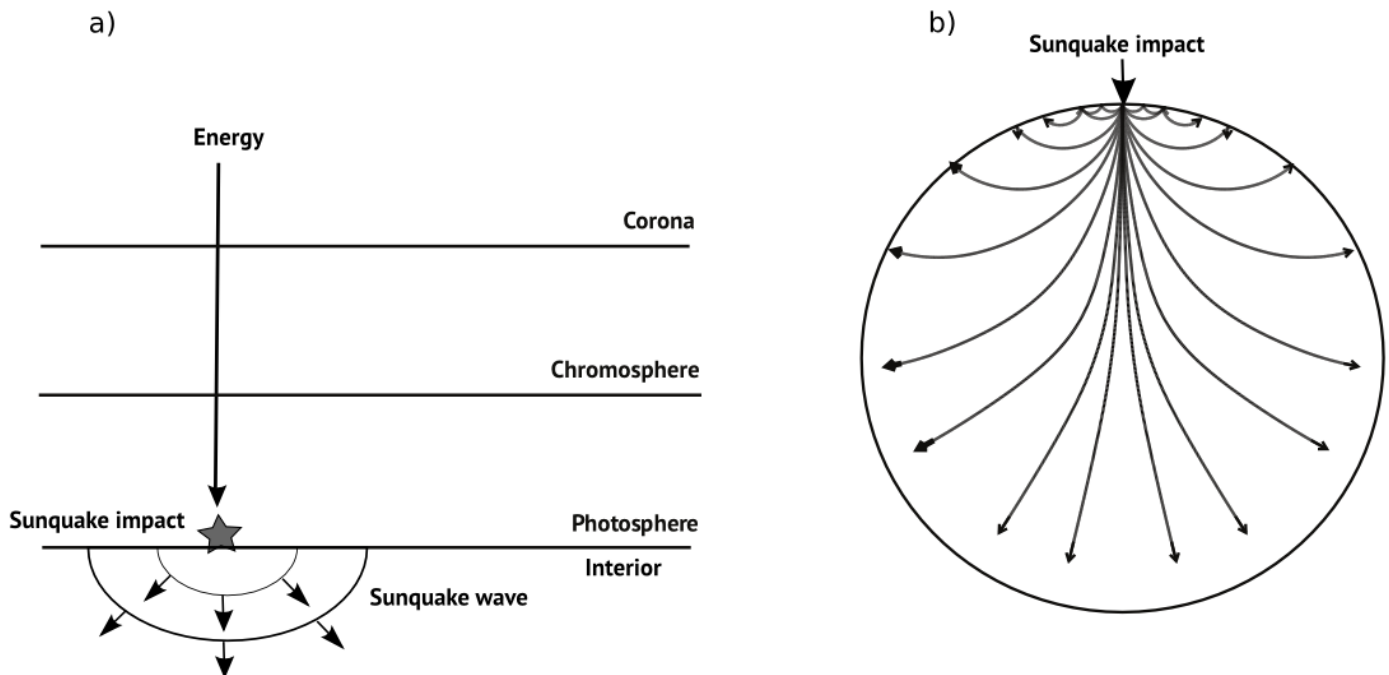


Figure 1: Sunquake cartoon: a) Shows a basic picture of sunquake production. Energy moves down through the solar atmosphere impacting the photosphere and generating a sunquake. b) Shows acoustic wave-fronts propagating into the interior of the Sun. Wave-fronts refract back toward the surface as they encounter increasingly dense sub-surface layers. Waves reaching the surface disturb material in a pattern resembling ripples in a pond. Courtesy of Kosovichev (2014)

1.2 Sunquake Observations

The idea that solar flares can cause acoustic waves inside the Sun was originally put forward by (Wolff, 1972). Wolff made the connection that a large solar flare releasing enough energy to heat the photosphere, would generate expansion of photospheric material, which could lead to an impulsive stimulation of oscillations in the Sun's interior. Wolff also commented that it would be difficult to observe interior oscillations with current (in the 1970s) solar velocity measurement techniques.

A little over twenty years later and Wolff's idea was built upon by Kosovichev and Zharkova (1995), who showed theoretically that acoustic waves in the solar interior could be generated by a large solar flare, and that they may be detectable. A year later and the first detection of a sunquake was made by Kosovichev and Zharkova (1998) during an X class solar flare on July the 9th 1996. Their observational data came from the Solar and Heliospheric Observatory (SOHO) via the Michelson Doppler Imager (MDI) which images the movement of photospheric material by analysing shifts in wavelength of the emitted light. They observed a prominent impulsive downward signature in the Dopplergrams directly over a compact point source which subsequently emanates a set of concentric acoustic waves (see Figure 2). The timing of maximum downward velocity of material derived from the Dopplergrams was out of sync with peak hard x-ray measurements by around a minute. This time delay, coupled with white-light enhancement in the lower atmosphere led to the conclusion that during the flare, accelerated energetic particles heat the cool dense chromosphere causing a shock front which travels downward, depositing energy in lower atmospheric layers, generating a sunquake.

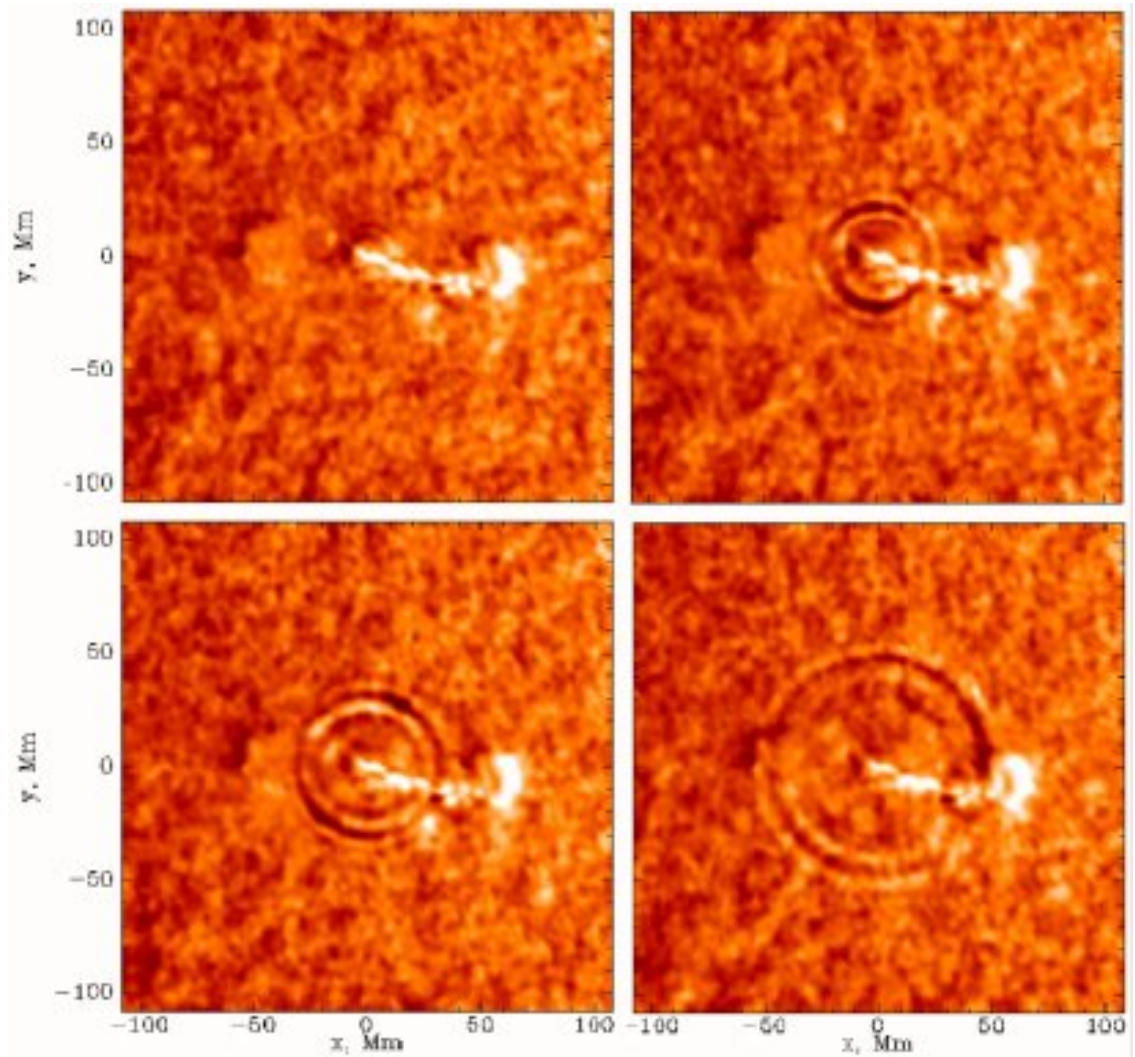


Figure 2: Kosovichev and Zharkova (1998) produced SOHO MDI Dopplergrams from the 1996 July 9th, X class solar flare showing the sunquake expanding outward from it's seismic epicentre to a radial distance of 1.2×10^8 metres. Wave-fronts accelerate from a velocity of 30km/s to 100km/s

The first sunquake observation opened up a whole new area of solar physics, leading to subsequent detections associated other flares. The majority of observations show that sunquakes are often the product of highly

impulsive flares, with the acoustic source aligning spatially with white light enhancement in the lower solar atmosphere and hard x-ray emission in the upper-atmosphere (Donea and Lindsey, 2005; Zharkova and Zharkov, 2007). Donea and Lindsey (2005) went on to calculate the energy needed to stimulate the propagation of an acoustic wave in the sub-photosphere, finding that only $\sim 10^{-3}$ of the energy released by a flare is enough to generate a sunquake. This was an important calculation because it forced the solar community to consider that it might be possible for low energy flares to produce sunquakes, leading to subsequent work by Martínez-Oliveros et al. (2008) looking at seismicity of M-class flares.

A paper by Hudson (2000) put forward for the first time, that sunquake production may depend on the changing configuration of the local magnetic field. This idea was further reinforced by Kosovichev and Zharkova (2001) reporting observations of impulsive changes in magnetic field strength at the photosphere during a solar flare. These magnetic transients were shown to approximately correlate in time and space with hard x-rays, impulsive increases in plasma velocity and increased emission. This line of study was continued (Martínez-Oliveros and Donea, 2009), investigating the magnetic field variation of the photosphere in many flares. The study found that some flares with seismicity do not have a spatial and temporal correlation between sunquakes and magnetic transients. Some flares have magnetic transients and no seismicity, and some flares have a good co-spatial alignment of acoustic activity and magnetic variability. It was noted that the impulsiveness of the magnetic field variation could be important as to whether a sunquake is generated.

Some of the most intriguing of sunquake observations are those that do not abide by the usual set of observable features, in that they are not necessarily associated with hard x-rays and excess white-light emission. For example, a statistical survey carried out by Pedram and Matthews (2012), highlighted a flare containing three footpoints with a seismic source that was co-temporal but not co-spatial with its closest HXR footpoint; and another source which was co-spatial and co-temporal with its nearest HXR footpoint. This showed that a sunquake does not necessarily correlate with locations of peak emission. Another example by Zharkov et al. (2011) reports an observation of two seismic sources associated with footpoints of an erupting flux rope. During the eruption, the magnetic field above each seismic source undergoes an abrupt permanent reconfiguration. The authors cite the possibility that there exists particle beams low enough in population that HXR emission is undetectable. Further papers investigating the same event (Zharkov et al., 2013) show that there are downward motions of material above the seismic sources and that energy provided by magnetic transients may not be able to account for the acoustic power generated. These observational oddities prove that mechanisms that generate sunquakes are not well understood and there is much research to be done to classify the different progenitors.

1.2.1 Sunquake Progenitors

The progenitors of sunquakes are still unknown and as a result this is an exciting area of research with discoveries still to be made. The general consensus, in terms of valid mechanisms that could cause this phenomenon is an area of contention, however the following progenitors are thought to be at least partly responsible.

- **Radiative backwarming** as a mechanism for producing sunquakes, was first put forward by Donea and Lindsey (2005) to account for a spatial correlation between seismic sources and white light emission from the lower atmosphere. During a solar flare, high energy electrons and photons impulsively heat the lower chromosphere or photosphere producing an enhancement in white light emission (Machado et al., 1989). This causes an impulsive increase in radiation pressure and gas pressure exerted on the photosphere, generating acoustic waves which propagate into the sub-photosphere.
- **Sudden magnetic field reconfiguration** was first detailed by Hudson et al. (2008). Solar flares are violent physical processes dictated by the interplay between reconnecting magnetic fields and charged solar plasma. Due to the Lorentz force, it is possible for a magnetic field to impart a force on a charged material and vice versa. If, during a solar flare, the magnetic field close to the photosphere relaxes to a more horizontal alignment it can impart a force on the photospheric material resulting in the production of acoustic waves, which propagate into the sub-photosphere. The key parameter for this mechanism seems to be that the field has to reconfigure in an sufficiently impulsive manner to generate enough force to induce seismic waves.
- **Shocks** are a mechanism originally proposed in initial work by Kosovichev and Zharkova (1995) and Kosovichev and Zharkova (1998), whereby a shock wave propagates from the upper-chromosphere down

to lower altitudes. During a solar flare, particles and heat are directed down toward the chromosphere, at which point chromospheric material reacts by increasing in temperature. This increased temperature causes explosive ablation of chromospheric material both upward and downward. The downward component develops into a shock front carrying energy to the lower atmosphere, which can go on to impact the photosphere generating acoustic waves. If the shock is dissipated at higher altitudes such as the lower chromosphere, heat generated during the deposition process can irradiate the photosphere with high energy photons, causing radiative backwarming (Machado et al., 1989).

- **Direct proton collision**, is linked to observations by Zharkova and Zharkov (2007) where the sunquake was spatially aligned with γ -ray emission. γ -rays during a solar flare are an indicator of energetic protons being accelerated along a newly reconfigured magnetic field. Proton beams carry more momentum than electron beams and are able to penetrate through the chromosphere to lower atmosphere. If an energetic beam of protons makes it down to the photosphere, it can deposit energy in the form of an impact, which due to conservation of momentum will generate acoustic waves in the sub-photosphere.

2 Eruptive Solar Flares

2.1 An Introduction to the Standard Eruptive Flare Model

Solar flares are the manifestation of magnetic energy release in the form of electromagnetic radiation spanning a wide range of wavelengths. These events are the most energetic phenomena associated with the Sun, with some of the larger flares releasing 10^{37} erg of energy. Flares are classified by the X-ray flux measured by the Geostationary Operational Environmental Satellite (GOES) see Table 1 below.

Classification	Peak Flux Range at 1 to 8 Å ($W.m^{-2}$)
X	$10^{-3} - 10^{-4}$
M	$10^{-4} - 10^{-5}$
C	$10^{-5} - 10^{-6}$
B	$10^{-6} - 10^{-7}$
A	$< 10^{-7}$

Table 1: shows the GOES flare classification, which is based on powers of ten of hard x-ray flux. X class flares are the most powerful and A class are the weakest.

The exact physical process governing the mechanics of solar flares is not known, however, magnetic reconnection is the currently accepted mechanism. Coronal magnetic loops tethered to sunspots of opposing polarity in the photosphere and sub-photosphere are twisted and stressed by movements of active regions across the solar surface. This shearing of the magnetic field, leads to the build up of magnetic free-energy. This energy can be released when opposing field lines meet and reconnect and the unstable tensioned magnetic field relaxing back to a more stable configuration. As a result stored magnetic energy is converted to radiation, kinetic and thermal energy. The standard 2D flare model is the culmination of research by many authors, (Carmichael, 1964; Sturrock, 1966; Hirayama, 1974; Kopp and Pneuman, 1976), and is still an ongoing area of research that is not entirely understood (Shibata and Magara, 2011). In an active region, a closed magnetic field harbouring a flux rope suddenly opens. As a result, plasma flows along the open field lines from the chromosphere to the corona. This flowing chromospheric material experiences a reduction in plasma pressure which draws together open magnetic field lines of opposing polarity causing reconnection and forming new magnetic loops at lower altitudes. Reconnection causes excess heating at the peaks of newly connected loops which conducts down toward the chromosphere. Also, particles are accelerated by the new magnetic configuration, flowing to the chromosphere. This injection of thermal energy and accelerated particles heats the chromosphere causing HXR footpoints (Aschwanden et al., 1995) and UV ribbons (Fletcher, 2009). As a result, some chromospheric material evaporates upward into newly created flare loops, whilst some material propagates downward toward the lower chromosphere. The flare loop cools and the process starts again in the next consecutive loop until the unstable magnetic field has relaxed to a state that is closer to its stable, potential state. In eruptive flares, energy is released every time a new reconnection of a neighbouring loop occurs, this is the reason that flare

ribbons appear move away from each other as the flare evolves.

White light flares (WLFs) are associated with the most energetic of solar flares. They occur when flare energy is transported deep into the dense lower atmosphere causing an enhancement in optical wavelengths. It is thought this happens due to an energetic particle beam transporting energy to the lower atmosphere where it's energy dissipates into the dense chromospheric or photospheric material. The collisional thick target model by Brown (1971) says that almost all of the flare energy is carried by the particle beam, therefore, energy dissipated in the lower atmosphere represents a large portion of the flare energy budget. White light enhancement from the lower atmosphere can be explained by either Balmer & Paschen continuum emission from the chromosphere caused by hydrogen recombination, or direct photospheric heating (Ding, 2007) by radiative backwarming (Machado et al., 1989).

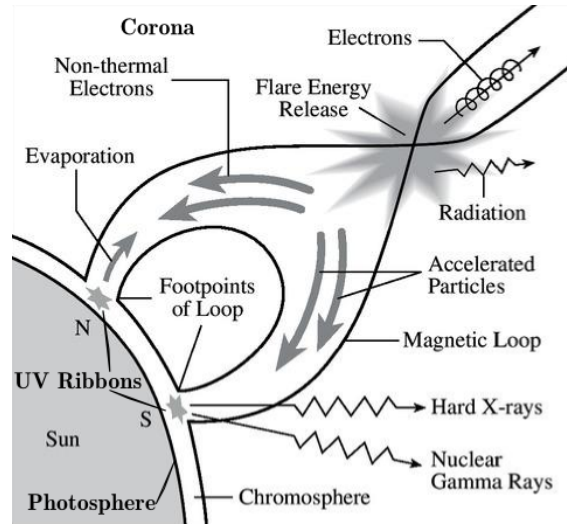


Figure 3: cartoon of the standard 2D solar flare model. Image courtesy of www.tufts.edu

2.1.1 Solar Atmosphere

The solar atmosphere is described as having four main components, the corona, transition region, chromosphere and photosphere, see Figure 4.

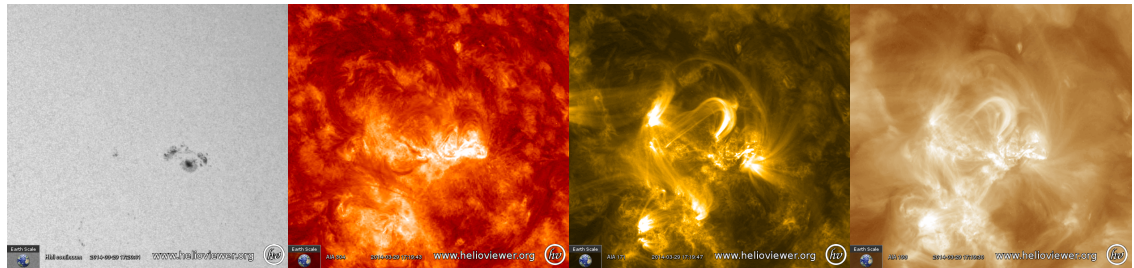


Figure 4: Images taken from the Solar Dynamics Observatory (SDO) instruments, the Helioseismic Magnetic Imager(HMI) and the Atmospheric Imaging Assembly (AIA) displaying the four main components of the solar atmosphere. From left to right layers of the solar atmosphere are increasing in altitude and temperature from the photosphere (SDO/HMI 6173 Å continuum), to the chromosphere (SDO/AIA 304 Å) through the transition region (SDO/AIA 171 Å) then up to the corona (SDO/AIA 193 Å). Images courtesy of www.helioviewer.org

For a sunquake to occur, energy released during a solar flare has to traverse these four layers propagating through nine pressure scale heights as it does so. Pressure scale height is a measure of the distance over which pressure drops off by a factor of e . For example, in the photosphere, $H \sim 150\text{km}$, whereas in the corona, $H \sim 100\text{Mm}$. The photosphere is where sunquakes form observable wave-fronts and is the lowest in altitude of the four layers. With an effective temperature of $T = 5800\text{K}$, the photosphere decreases in temperature with radial distance. If white light enhancement is observed in the photosphere, it is thought to be an indicator of the **Radiative backwarming** progenitor of sunquake generation, which can also be a bi-product caused by

chromospheric **Shocks**. The plasma beta (a measure of the ratio between gas and magnetic pressure) in this region is mostly larger than one, $\beta > 1$, meaning plasma pressure is dominant in dictating plasma motions, the exception to this exists in sunspots where $\beta < 1$ and magnetic pressure is dominant.

Found in active regions of the photosphere, sunspots are regions of intense magnetic field playing host to footpoints of loops that can extend out into interplanetary space. They are made up of two main parts, the dark central umbra, surrounded by the slightly less dark penumbra. The umbra hosts magnetic field lines that are tightly packed and pointing radially away from the Sun, whereas the penumbral magnetic field is more horizontal with respect to the solar surface. During a solar flare, coronal loops reconnect causing a reconfiguration of the magnetic field tethered at sunspot locations, at this point, penumbral field lines can collapse toward the photosphere, imparting a Lorentz force on local plasma. This leads to the **Sudden magnetic field reconfiguration** progenitor of sunquake generation. Other features that are found on the photosphere include granules, which are the physical representation of convection currents. Heated plasma rises from below the surface and is seen as the bright central part of the granule, the darker surrounding regions are cooler material sinking back into the interior.

The next region of the atmosphere is the chromosphere which is situated above the photosphere. This layer of plasma is a few thousand kilometres (2000-3000km) thick and is optically thin to visible light so is difficult to see against the brightness of the photosphere. The temperature in this layer increases with height and ranges from 4400K at the temperature minimum region to $\sim 10^5$ K at the top, as a result, β drops rapidly crossing unity as it does so. The pressure scale height in this region is changing with altitude. Through the transition region to the corona and the atmosphere starts to heat considerably to $T \sim 10^7$ K. This region is visible in white light due to Thompson scattering of photospheric light by free electrons and dust in the coronal magnetic field. The plasma beta is less than one through the entire corona meaning magnetic forces dominate. Figure 5 shows how the solar atmosphere changes with height, temperature and density, giving an indication of the stratification of atmospheric layers. Information in this section is taken from text books: Dwivedi and Parker (2003); Foukal (2004)

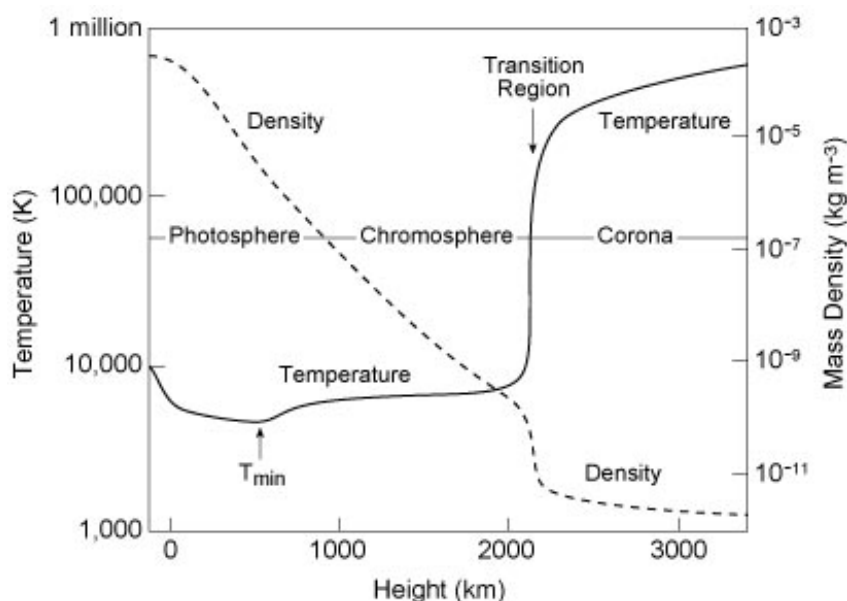


Figure 5: The temperature of the solar atmosphere decreases from values near 6,000 degrees Kelvin at the visible photosphere to a minimum value of roughly 4,400 degrees Kelvin about 500 kilometres higher up. The temperature increases with height, slowly at first, then extremely rapidly in the narrow transition region, less than 100 kilometres thick, between the chromosphere and corona, from about 10^4 K to about 10^6 K. (Courtesy of Eugene Avrett, Smithsonian Astrophysical Observatory.)

2.2 Observing Solar Flares

Using data collected by spacecraft observing the Sun, energy released during solar flares can be tracked as it is deposited throughout the atmosphere. Energy deposition in the upper chromosphere is marked by HXR

footpoints and UV ribbons. The Ramaty High Energy Solar Spectroscopic Imager (RHESSI) observes solar emission ranging from X-rays to γ -rays produced by energetic particles and nuclear interactions. RHESSI was designed with the aim of understanding impulsive energy release, particle acceleration and transportation in the magnetohydrodynamic environment of the solar atmosphere. Using 25 - 50 keV and 50 - 100 keV intensity data collected by RHESSI, HXR footpoints can be tracked and analysed.

Observing UV ribbons requires a different spacecraft. The Interface Region Spectroscopic Imager (IRIS) captures near-ultraviolet (NUV) and far-ultraviolet (FUV) emission and is designed to observe the chromosphere at various altitudes. Emission is collected by a slit-jaw imager (SJI) and a spectrometer (SG) simultaneously. The spectrograph is sensitive in both FUV and NUV passbands, which expose 3 CCDs to produce spectra in three UV bands, two FUV and one NUV. Table 2 shows how each passband relates to emission processes occurring from the upper-chromosphere down to the upper-photosphere.

Band	Wavelength \AA	Temperature $\log T$	Region of Atmosphere
FUV 1	1331.7 – 1358.4	3.7 – 7.0	Upper to lower-chromosphere
FUV 2	1389.0 – 1407.0	3.7 – 5.2	Upper to lower-chromosphere
NUV	2782.7 – 2851.1	3.7 – 4.2	Chromosphere to upper-photosphere

Table 2: The IRIS/SG is capable of observing three passbands, which relate to different plasma temperatures.

The slit-jaw images, are light collected from a reflective area surrounding the slit. The imager is capable of observing four wavelengths relating to emission at different altitudes as shown by Table 3.

SJI Passband	Wavelength \AA	FWHM \AA	Temperature $\log T$	Region of Atmosphere
C II	1330	40	3.7 – 7.0	Upper-chromosphere
Si IV	1400	40	3.7 – 5.2	Upper-chromosphere
Mg II h/k	2796	4	3.7 – 4.2	Lower-chromosphere
Mg II wing	2832	4	3.7 – 3.8	Upper-photosphere

Table 3: The IRIS/SJ is capable of observing four passbands, which relate to different plasma temperatures.

Signatures from energy deposition in the lowest regions of atmosphere are captured by Solar Dynamics Observatory’s (SDO) Helioseismic Imager (HMI), which observes the photosphere. Able to observe optical continuum intensity (6173 \AA), helioseismic and magnetic data, SDO/HMI can provide valuable insight into WLFs, sunquakes and magnetic field configuration. Optical continuum data can provide information about WLFs and radiative backwarming of photospheric material, which is a possible sunquake progenitor. Helioseismic data can be used to analyse the movement of material during a solar flare, such as downward flows which could indicate shocks propagating from higher altitudes or particle beams penetrating the atmosphere. The point of origin and wave-fronts of a sunquake can also be detected using helioseismic data, which can be used to calculate acoustic power of the quake. Magnetic data from SDO/HMI shows local magnetic field direction, useful for determining the presence of impulsive changes in magnetic field capable of generating a sunquake.

2.3 Observable Seismic Signatures

Helioseismology is a tool for probing the interior of the Sun. Most techniques in this field of analysis rely on observations of gravity and acoustic waves on the photosphere that are the result of interior excitation. Studying the frequency and modes of these oscillations has revealed much about the internal structure of the Sun. Local helioseismology is a collection of techniques developed for global helioseismology that have been modified for use in studying local regions in higher spatial resolution. The following section provides a very basic introduction to some of these techniques.

2.3.1 Local Helioseismology

Helioseismic Holography Donea et al. (1999) pioneered the use of helioseismic holography to produce seismic images of the solar flare of July 1996 reported to have a sunquake by Kosovichev and Zharkova. Time series egression-power maps at 3.5 and 6 mHz were computed with a 2 mHz bandwidth. It was found that the most powerful acoustic power frequency associated with the flare is centred at 3.5 mHz but has a large amount of noise. However, the 6 mHz range has a much lower ambient noise, therefore producing a better rendering

of the seismicity of the flare. It is now standard practice to use the 6 mHz range for helioseismic holographic calculations of egression-power.

Originally the idea of analysing Doppler images of the solar surface in order to observe acoustic sources was put forward by Roddier (1975). Helioseismic holography was developed further in concept by Lindsey and Braun (Lindsey and Braun, 1990; Braun et al., 1992; Lindsey and Braun, 1997) in an effort to to image the solar interior and far-side of the Sun. This technique involves using a Doppler image of a location on the solar surface as a reference wave-field to enable an estimation of that wave-field at a location in the solar interior at a time preceding or proceeding the image. This is achieved by calculating the ingression or egression of the wave-field by assuming that it's evolution is a, convergence to, or divergence from, the point of origin of that wave-field. The technique uses Green's function (eqn 1, where \mathbf{r} and t are position and time of an observed signal and \mathbf{r}' and t' are the position and time of the signal earlier in time) which assumes that the acoustic wave propagates from a point source, allowing a signal $\psi(\mathbf{r}, t)$ observed on the surface to be devolved backwards in time.

$$G_+(|\mathbf{r} - \mathbf{r}'|, t - t') \quad (1)$$

Where a and b constrain the holographic pupil, equation 2 is then used to devolve the surface signal to calculate the position of subsurface acoustic sources.

$$H_+(\mathbf{r}, z, t) = \int dt' \int_{a < |\mathbf{r} - \mathbf{r}'| < b} d^2\mathbf{r}' G_+(|\mathbf{r} - \mathbf{r}'|, t - t') \psi(\mathbf{r}', t') \quad (2)$$

Equation 3 is then used to calculate the egression power associated with the acoustic sources at a time t .

$$P(z, \mathbf{r}) = \int dt |H_+(\mathbf{r}, z, t)|^2 dt \quad (3)$$

If egression power is required in terms of frequency then equation 3 can be Fourier transformed into frequency space.

Time-Distance The first observation of a sunquake (Kosovichev and Zharkova, 1998) used the time-distance technique to track sunquake wavefronts. The paper by Duvall et al. (1993) explains how to extract time-distance (TD) information from observations of intensity fluctuations on the solar surface. This technique uses travel times of waves between two locations on the solar surface. The method assumes that the travel time of a wave propagating in the interior of the Sun will be modified by any anomalies that it has to travel through, thus the resulting signal will contain the signatures of those irregularities. For instance, if the wave encounters a flow along it's path of travel, it will propagate faster with the flow than against it, affecting travel time. This technique remaps Dopplergrams into polar coordinates, with the point of origin centred on the area of downflowing material during the flare. This remapped image is then Fourier transformed with respect to azimuthal angle, with the resulting image highlighting circular disturbances as a line of positive slope.

3 Lower Atmospheric Solar Flare Signatures Associated with Seismicity

3.1 Background

Sunquakes represent the propagation of acoustic waves in the sub-photosphere, responding to an excitation of the photosphere during the impulsive phase of solar flares. The progenitors of sunquakes are thought to be either shocks, radiative backwarming, direct proton collision or sudden magnetic field reconfiguration, see Section 1.2.1. Each of these mechanisms relies on the transport of energy from the corona to the photosphere, and the physical conditions existing in the chromosphere such as magnetic field configuration and plasma density. To understand sunquakes and their relationship to solar flares, we need to understand how energy moves down through the solar atmosphere and the physical conditions that are present.

The majority of the energy released by a flare is deposited in the lower solar atmosphere and manifests itself in the form of enhanced hard X-ray, UV and optical radiation. During the impulsive phase of a solar flare, energy in the form of energetic particles, shocks and MHD waves flow along newly formed coronal magnetic loops, down through the stratified solar atmosphere. As energy is deposited through the differing environments of each atmospheric layer, telltale emission signatures are released. Hard X-ray (HXR) footpoints are observed due to the excitation of the chromosphere by energetic particle beams accelerated by the reconnecting magnetic field in the corona during the flare (Aschwanden et al., 1995). According to the standard flare model (Carmichael, 1964; Sturrock, 1966; Hirayama, 1974; Kopp and Pneuman, 1976) magnetic reconnection in the corona leads to energy being directed downward in the form of particles, radiation, MHD waves and conduction of heat, which in turn produces ultra-violet (UV) ribbons in the chromosphere. This means that HXR footpoints and UV ribbons observed in the chromosphere directly map to the reconfiguring magnetic fields during the flare. As energy moves down through the chromosphere toward the photosphere, emission becomes visible in the optical, known as a white light flare (WLF). The processes governing WLF emission in the lower solar atmosphere are detailed by Ding (2007) whereby two main mechanisms are highlighted; Balmer/Paschen continuum emission produced via hydrogen recombination in the lower chromosphere; and enhancement of photospheric continuum emission due to heating of the temperature minimum region. According to Machado et al. (1989), Balmer/Paschen emission upward (i.e., directly detected) also has a downward component which leads to impulsive radiative backwarming of the photosphere which in-turn can generate a sunquake.

3.2 Observations

The X1 flare of the 29th of March 2014 in active region NOAA 12017, was well observed by RHESSI, IRIS and SDO/HMI, collecting HXR, UV and optical emission respectively. The impulsive phase of the flare occurs at 17:46 UT, at which point all mentioned instruments provide good coverage. RHESSI captured hard x-ray data throughout the flare, this data is primarily used to mark the injection site of accelerated energetic particles in the upper-chromosphere. Contour maps of HXRs at energy ranges of 25 - 50 and 50 - 100 keV are aligned with IRIS, SDO/HMI, and acoustic power data to demonstrate co-spatial alignment of data-sets, see Figure 6. The IRIS spacecraft captured the temporal evolution of the flare between 14:09 and 17:54 UT via its slit-jaw imager and spectrograph instruments at solar coordinates of 491", 282" with a spatial resolution of 0.1667" per pixel. The slit-jaw imager data provides coverage of a field of view spanning 167" by 174", of passbands that including 1403, 2796 and 2832 Å at 26, 19 and 75 second cadence respectively. The spectrograph slit is aligned directly over chromospheric flare ribbons, and the sunquake point of origin, with a field of view spanning 14" by 174". The spectrograph slit is exposed for ~ 9 seconds at 8 slit locations for a total of 72 seconds cadence. Wavelengths observed over three channels include FUV1: 1331.7 - 1358.4 Å, FUV2: 1389.0 - 1407.0 Å and NUV: 2782.7 - 2851.1 Å, associated with the upper-chromosphere down to the upper-photosphere. Spectral lines include C II, Si IV and Mg II h and k. IRIS data is the standard level 2 data product provided for scientific research, which has been calibrated to negate dark currents, flat-field and spacecraft rotational effects. The HMI instrument onboard SDO observed the entire solar photosphere, collecting 6173 Å continuum intensity data throughout the flare event. HMI has a pixel size of 0.6 " providing reasonable spatial resolution at a cadence of 45 seconds. HMI data is calibrated to negate cosmic-rays, dark currents, flat-field and spacecraft rotational effects. A 6mHZ acoustic egression power map, generated via holography techniques, is supplied via private communication by Sergei Zharkov.

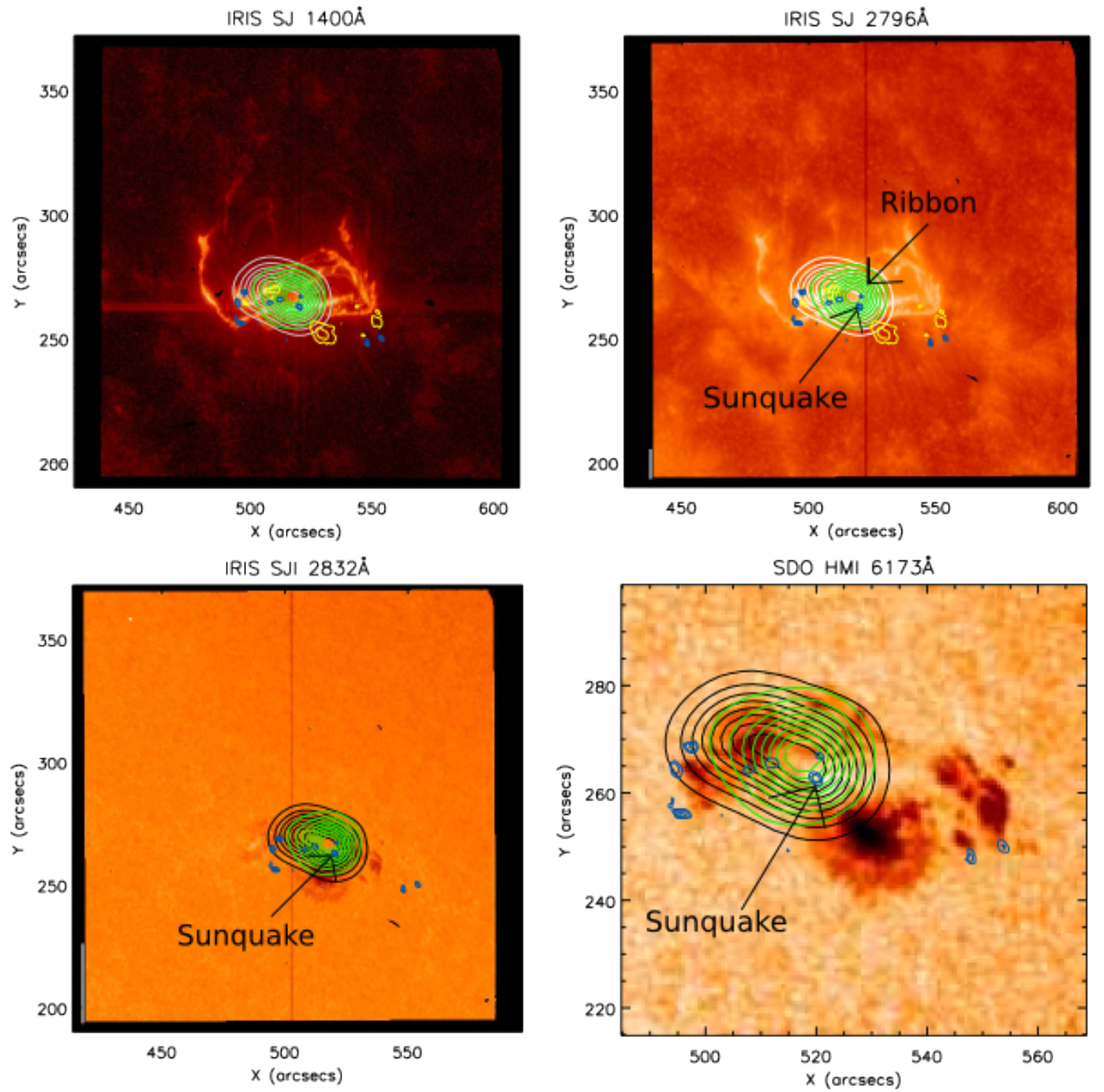


Figure 6: From top left to bottom right, images represent regions of the solar atmosphere at descending altitudes. The top two and bottom left images show IRIS SJ intensity maps of 1403\AA (transition Region), 2796\AA (chromosphere) and 2832\AA (upper-photosphere) data. The bottom right image is SDO HMI 6173\AA continuum intensity from the photosphere. Contours show RHESSI HXR with $E = 25 - 50\text{ keV}$ in white or black and HXR with $E = 50 - 100\text{ keV}$ in green, sunspot locations in yellow taken from HMI and 6mHz acoustic power in blue.

3.3 Analysis

White light flares are difficult to see against the bright photospheric background therefore SDO HMI data is subjected to a running difference filter to isolate locations that are white-light enhanced. The running difference filter effectively removes static features leaving behind those pixels that are changing over short time-scales. This is not a perfect process, tending to also highlight granulation features on the photosphere. The next stage is to determine which pixels in the difference image are those that are enhanced during the flare. These white-light enhanced pixels are identified using a combination of visual inspection and thresholding to eliminate false positives being triggered by noise or granulation features. IRIS SJIs and SG data have no need for filtering.

SJIs of Si IV, Mg II and Mg II wing that are aligned with HMI data and lightcurves are created for pixels at sunquake and ribbon locations. Lightcurves are also created from IRIS spectroscopic data at slit positions aligned with quake and ribbon locations, over a wavelength range of 2825.7 and 2825.8 Å within the Balmer continuum which are also aligned with IRIS SJI and HMI data (see Figure 7). The same IRIS SJ data is converted from DN per pixel to $erg.s^{-1}.cm^{-2}.Å^{-1}.sr^{-1}$ intensity units, by using recently released conversion factors, which will eventually be used to calculate the amount of energy being deposited in the chromosphere and upper photosphere (see Figure 8).

IRIS spectroscopic data are produced at sunquake, ribbon and non-flaring positions (see Figure 3.3. An egression map of acoustic power at 6mHz, reveals the position of the sunquake. HXR data from RHESSI and acoustic power data are overlaid on HMI and IRIS slit jaw maps to highlight spatial and temporal evolution of data-sets (see Figure 6).

3.4 First Results and Discussion

The location of maximum acoustic power, RHESSI HXR, IRIS and SDO intensity correlate both spatially and temporally (see Figure 6), showing that energy input into the upper chromosphere somehow propagates down to the photosphere. The sunquake is located directly underneath both maximum HXR and white-light emission.

Intensity lightcurves (see Figure 7) from SDO and IRIS seem to suggest a similar representation of the movement of energy through the chromosphere to lower altitudes, since their impulsive appearance and peak intensity occur within a minute of each other throughout the different regions. In the transition region above the chromosphere, relative intensity values at both sunquake and ribbon locations increase by three orders of magnitude during the impulsive phase of the flare. The double-peak feature is discussed below. In the chromosphere, relative intensity values at both sunquake and ribbon locations increase by two orders of magnitude during the impulsive phase of the flare. IRIS Balmer light curves for both locations increase by around 100% during the flare indicating the existence of radiative backwarming, however, initial values are very different. Pre-flare Balmer emission in the sunquake location is four times that in the ribbon location, this could indicate that radiative backwarming is more prolific above the sunquake, providing a source of further study. Similarly to the Balmer lightcurves, the upper-photosphere data shows the pre-flare sunquake location intensity to be approximately one order of magnitude greater than in the ribbon. Both locations show an order of magnitude increase in relative intensity during the flare. SDO HMI data from the photosphere shows both sunquake and ribbon data-sets display an order of magnitude increase in intensity during the flare, although it seems that the ribbon location has a larger increase.

IRIS SJI lightcurves converted into $erg.s^{-1}.cm^{-2}.Å^{-1}.sr^{-1}$ show the emission flux increase during the flare. In the transition region above the chromosphere intensity increases by three orders of magnitude, from 10^{11} to $10^{14} erg.s^{-1}.cm^{-2}.Å^{-1}.sr^{-1}$, in both sunquake and ribbon locations. When compared to the ribbon plot, the sunquake location displays an interesting double-peak which seems to suggest that there is a preliminary deposition of energy approximately 7 minutes before the onset of the impulsive phase of the flare. The energy deposited and highlighted by the first of the two peaks could provide a means to lower the density in the upper-chromosphere by causing chromospheric material to expand upward and downward. The resulting downward propagating shock wave could leave an easier path for energy transport during the main flare impulse, allowing penetration to deeper atmospheric layers. This is an idea that will be investigated in more detail in the future. In the chromosphere intensity increases by two order of magnitude, from 10^{11} to $10^{13} erg.s^{-1}.cm^{-2}.Å^{-1}.sr^{-1}$, in both sunquake and ribbon locations. In the upper-photosphere intensity increases by one order of magnitude, from 10^{12} to $10^{13} erg.s^{-1}.cm^{-2}.Å^{-1}.sr^{-1}$, in both sunquake and ribbon locations. As described above, pre-flare intensity values differ between the two locations.

Spectroscopic data shown in Figure 3.3 show the sunquake emission to be an order of magnitude greater in amplitude than in the ribbon. The spectrum taken from a non-flaring region is around three orders of magnitude smaller than the sunquake location. This means that the sunquake location is receiving more energy during the flare than both the ribbon and non-flare locations. Lines over the sunquake location are strongly broadened when compared to spectra elsewhere, which could indicate heating or increased pressure in these regions. Ribbon and sunquake spectra appear to be redshifted in comparison to the non-flaring region, showing that there must be material moving down through the chromosphere during the flare.

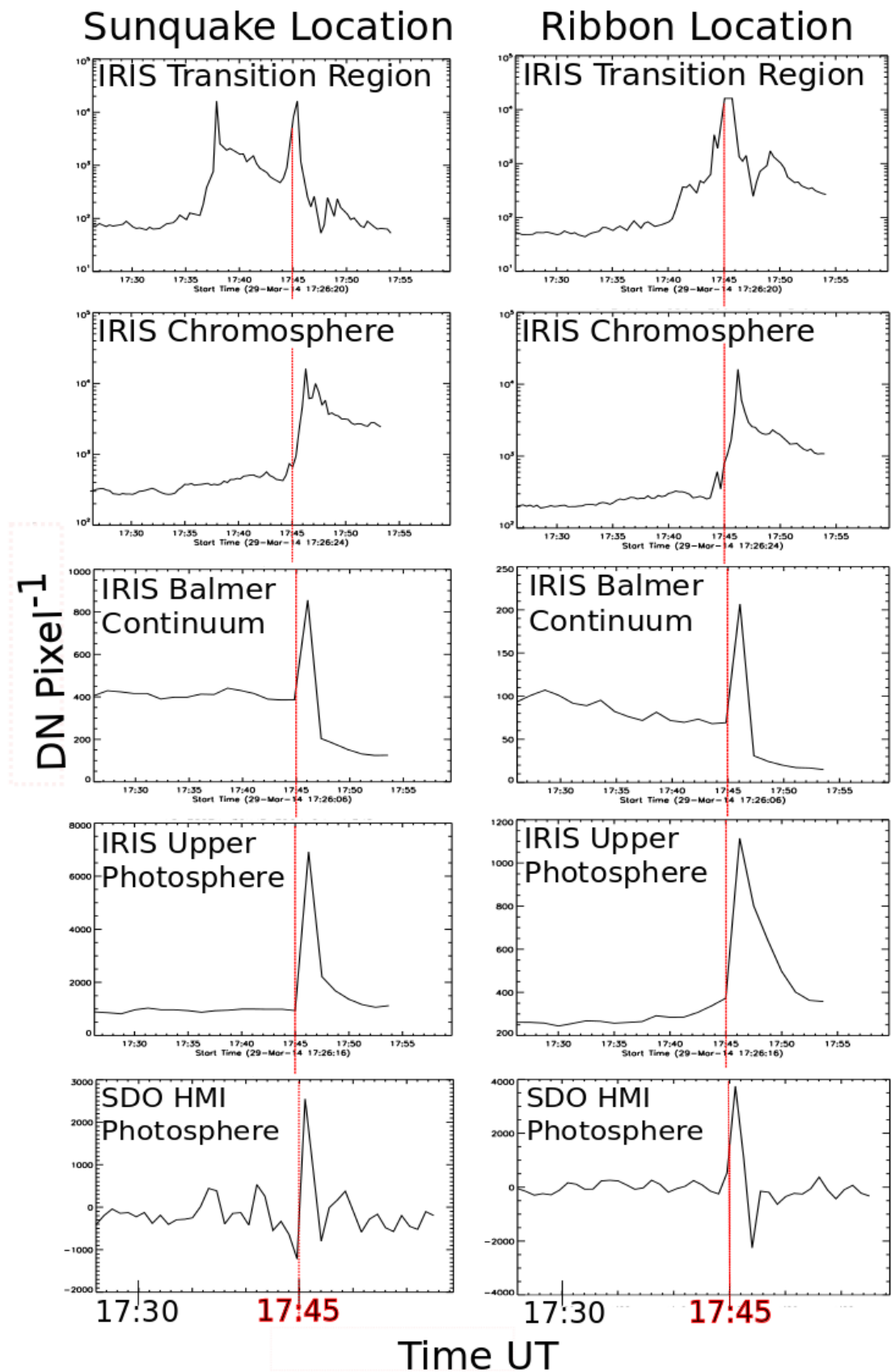


Figure 7: Left panel shows data over the quake location, right panel shows data over the ribbon location. From top to bottom, plots show lightcurves from IRIS Si IV, Mg II, Balmer wavelengths and Mg II wing, with the bottom panel showing the lightcurve from SDO HMI.

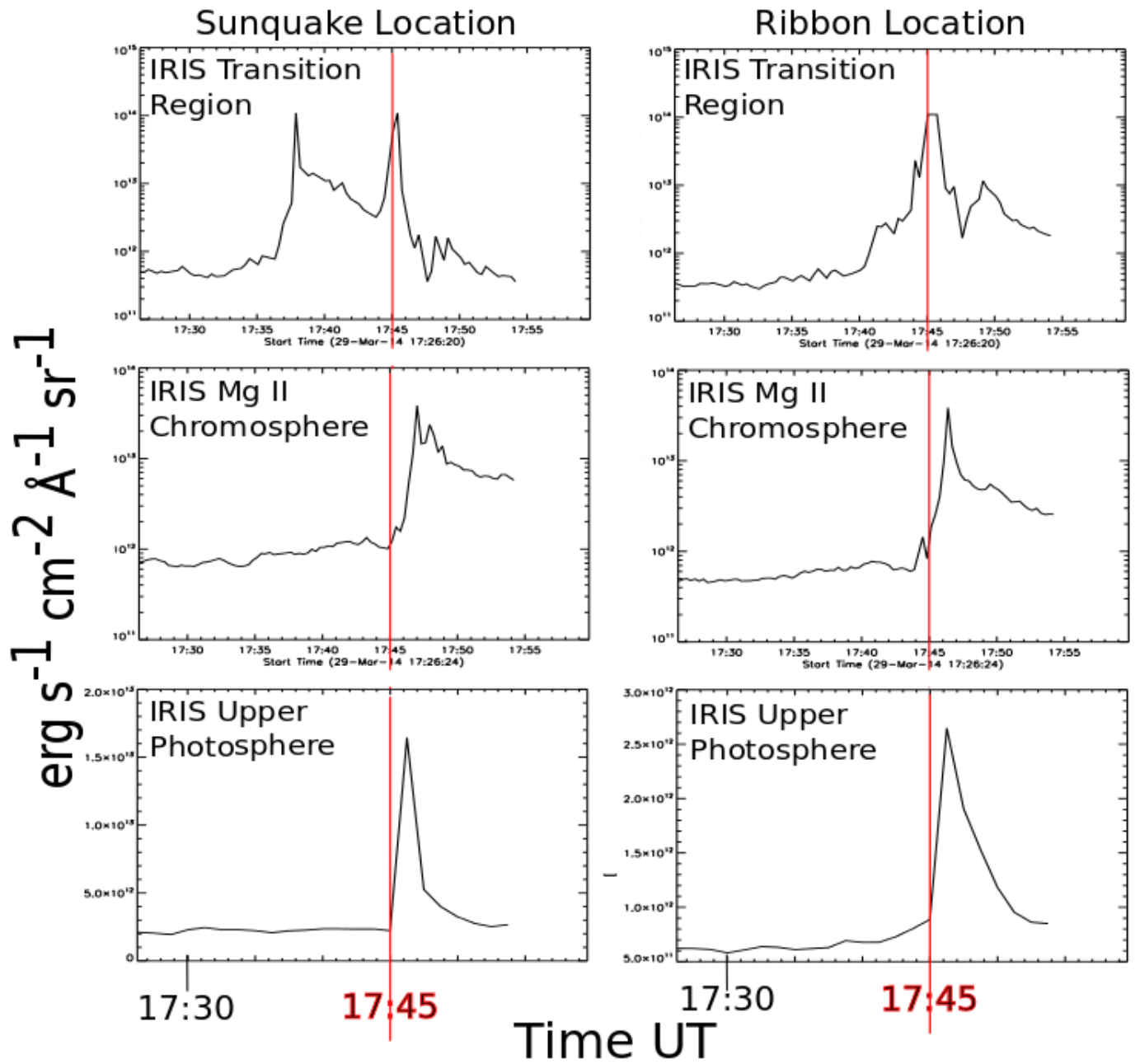


Figure 8: Left panel shows data over the quake location, right panel shows data over the ribbon location. From top to bottom, plots show lightcurves from IRIS Si IV, Mg II and Balmer wavelengths, with intensity converted into flux units relevant for energy calculations.

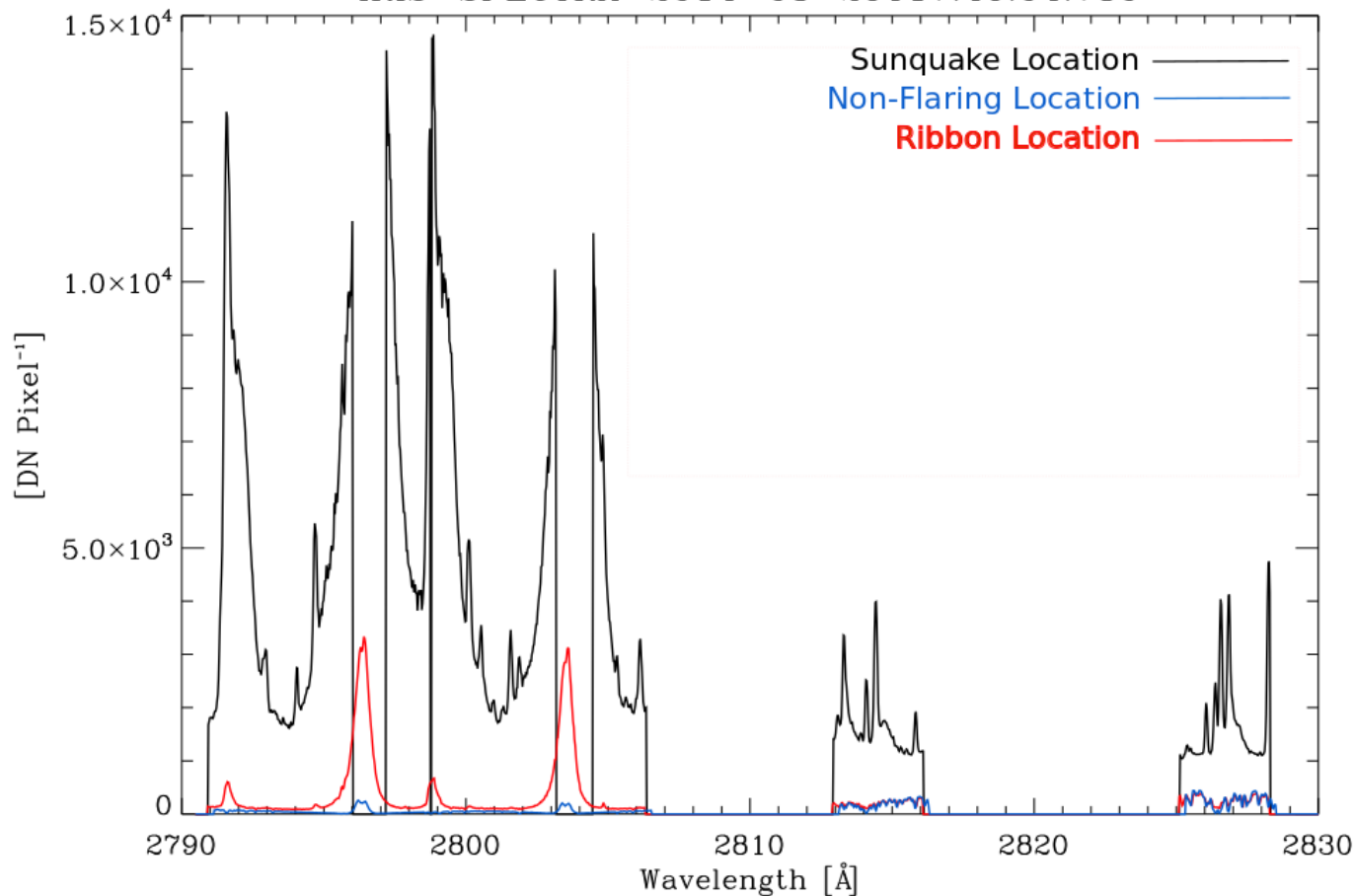


Figure 9: IRIS spectroscopic data ranging in wavelength 2796 - 2830 \AA . Black is the spectrum at the quake location, red is the spectrum at a point along the ribbon and blue is the spectrum of a non-flaring region. Square trough like features represent saturation of the CCD. The sunquake and ribbon locations have increased amplitude and are strongly redshifted and broadened.

3.5 Future Work

In the next three to six months the aim is to have completed the following tasks:

- Calculate energy associated with emission captured by HMI to compare with the acoustic power of the sunquake.
- Calculate energy associated with emission captured by IRIS slit jaw and spectrometer in order to estimate energy deposition in the atmosphere.
- Calculate energy associated with Balmer emission to assess likely energy contribution of radiative back-warming.
- Calculate non-thermal electron power via HXR spectra to estimate the initial energy of the electron beam accelerated by the corona.
- A more detailed analysis of IRIS spectroscopic data to estimate velocity, density and temperature of chromospheric material.
- Analysis of triplet lines in the wings of Mg II h & k will be used to determine heating of the lower chromosphere as per recent work by Pereira et al. (2015).
- Compare spectroscopic data taken by EIS with that of IRIS.
- Magnetogram: Look at HMI/SOT data to analyse the configuration of the magnetic field.
- Learn how to apply local helioseismology techniques to data.

References

- M. J. Aschwanden, A. O. Benz, B. R. Dennis, and R. A. Schwartz. Solar Electron Beams Detected in Hard X-Rays and Radio Waves. *ApJ*, 455:347, December 1995. doi: 10.1086/176582.
- D. C. Braun, C. Lindsey, Y. Fan, and S. M. Jefferies. Local acoustic diagnostics of the solar interior. *ApJ*, 392: 739–745, June 1992. doi: 10.1086/171477.
- J. C. Brown. The Deduction of Energy Spectra of Non-Thermal Electrons in Flares from the Observed Dynamic Spectra of Hard X-Ray Bursts. *Sol. Phys.*, 18:489–502, July 1971. doi: 10.1007/BF00149070.
- H. Carmichael. A Process for Flares. *NASA Special Publication*, 50:451, 1964.
- M. D. Ding. The Origin of Solar White-Light Flares. In P. Heinzel, I. Dorotovič, and R. J. Rutten, editors, *The Physics of Chromospheric Plasmas*, volume 368 of *Astronomical Society of the Pacific Conference Series*, page 417, May 2007.
- A.-C. Donea and C. Lindsey. Seismic Emission from the Solar Flares of 2003 October 28 and 29. *ApJ*, 630: 1168–1183, September 2005. doi: 10.1086/432155.
- A.-C. Donea, D. C. Braun, and C. Lindsey. Seismic Images of a Solar Flare. *ApJ*, 513:L143–L146, March 1999. doi: 10.1086/311915.
- T. L. Duvall, Jr., S. M. Jefferies, J. W. Harvey, and M. A. Pomerantz. Time-distance helioseismology. *Nature*, 362:430–432, April 1993. doi: 10.1038/362430a0.
- B. N. Dwivedi and F. b. E. N. Parker. *Dynamic Sun*. Cambridge University Press, Cambridge, UK, May 2003.
- L. Fletcher. Ultra-violet footpoints as tracers of coronal magnetic connectivity and restructuring during a solar flare. *A&A*, 493:241–250, January 2009. doi: 10.1051/0004-6361:20077972.
- P. V. Foukal. *Solar Astrophysics, 2nd, Revised Edition*. Wiley-VCH, 2004.
- T. Hirayama. Theoretical Model of Flares and Prominences. I: Evaporating Flare Model. *Sol. Phys.*, 34:323–338, February 1974. doi: 10.1007/BF00153671.
- H. S. Hudson. Implosions in Coronal Transients. *ApJ*, 531:L75–L77, March 2000. doi: 10.1086/312516.
- H. S. Hudson, G. H. Fisher, and B. T. Welsch. Flare Energy and Magnetic Field Variations. In R. Howe, R. W. Komm, K. S. Balasubramaniam, and G. J. D. Petrie, editors, *Subsurface and Atmospheric Influences on Solar Activity*, volume 383 of *Astronomical Society of the Pacific Conference Series*, page 221, 2008.
- R. A. Kopp and G. W. Pneuman. Magnetic reconnection in the corona and the loop prominence phenomenon. *Sol. Phys.*, 50:85–98, October 1976. doi: 10.1007/BF00206193.
- A. G. Kosovichev. Sunquakes: helioseismic response to solar flares. *ArXiv e-prints*, February 2014.
- A. G. Kosovichev and V. V. Zharkova. Seismic Response to Solar Flares: Theoretical Predictions. In *Helioseismology*, volume 376 of *ESA Special Publication*, page 341, 1995.
- A. G. Kosovichev and V. V. Zharkova. X-ray flare sparks quake inside Sun. *Nature*, 393:317–318, May 1998. doi: 10.1038/30629.
- A. G. Kosovichev and V. V. Zharkova. Magnetic Energy Release and Transients in the Solar Flare of 2000 July 14. *ApJ*, 550:L105–L108, March 2001. doi: 10.1086/319484.
- C. Lindsey and D. C. Braun. Helioseismic imaging of sunspots at their antipodes. *Sol. Phys.*, 126:101–115, March 1990. doi: 10.1007/BF00158301.
- C. Lindsey and D. C. Braun. Helioseismic Holography. *ApJ*, 485:895–903, August 1997.
- M. E. Machado, A. G. Emslie, and E. H. Avrett. Radiative backwarming in white-light flares. *Sol. Phys.*, 124: 303–317, September 1989. doi: 10.1007/BF00156272.

- J. C. Martínez-Oliveros and A.-C. Donea. Magnetic field variations and seismicity of solar active regions. *MNRAS*, 395:L39–L42, May 2009. doi: 10.1111/j.1745-3933.2009.00637.x.
- J. C. Martínez-Oliveros, H. Moradi, and A.-C. Donea. Seismic Emissions from a Highly Impulsive M6.7 Solar Flare. *Sol. Phys.*, 251:613–626, September 2008. doi: 10.1007/s11207-008-9122-y.
- E. Pedram and S. A. Matthews. A Survey of the Hard X-Ray Characteristics of Seismically Active and Quiet White-Light Flares. *Sol. Phys.*, 277:317–335, April 2012. doi: 10.1007/s11207-011-9922-3.
- T. M. D. Pereira, M. Carlsson, B. De Pontieu, and V. Hansteen. The Formation of IRIS diagnostics. IV. The Mg II triplet lines as a new diagnostic for lower chromospheric heating. *ArXiv e-prints*, April 2015.
- F. Roddier. Principle of production of an acoustic hologram of the solar surface. *Academie des Sciences Paris Comptes Rendus Serie B Sciences Physiques*, 281:93–95, July 1975.
- K. Shibata and T. Magara. Solar Flares: Magnetohydrodynamic Processes. *Living Reviews in Solar Physics*, 8:6, December 2011. doi: 10.12942/lrsp-2011-6.
- P. A. Sturrock. Model of the High-Energy Phase of Solar Flares. *Nature*, 211:695–697, August 1966. doi: 10.1038/211695a0.
- C. L. Wolff. Free Oscillations of the Sun and Their Possible Stimulation by Solar Flares. *ApJ*, 176:833, September 1972. doi: 10.1086/151680.
- S. Zharkov, L. M. Green, S. A. Matthews, and V. V. Zharkova. 2011 February 15: Sunquakes Produced by Flux Rope Eruption. *ApJ*, 741:L35, November 2011. doi: 10.1088/2041-8205/741/2/L35.
- S. Zharkov, L. M. Green, S. A. Matthews, and V. V. Zharkova. Properties of the 15 February 2011 Flare Seismic Sources. *Sol. Phys.*, 284:315–327, June 2013. doi: 10.1007/s11207-012-0169-4.
- V. V. Zharkova and S. I. Zharkov. On the Origin of Three Seismic Sources in the Proton-rich Flare of 2003 October 28. *ApJ*, 664:573–585, July 2007. doi: 10.1086/518731.