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A study of photospheric vector magnetic field changes during solar flares

Master Thesis project
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1 Introduction

This master thesis will study the magnetic changes during explosive atmospheric processes on the Sun which are called *flares*. Flares have been studied by different authors during the last century due to their importance for solar energetics and processes (e.g. particles acceleration, magnetic fields, cooling and heating processes, mass movements Benz (2008); Shibata and Magara (2011); Hudson (2011)), in the solar interiors (e.g. sunquakes Kosovichev and Zharkova (1998); Alvarado-Gómez *et al.* (2012)) and the space weather, e.g. their correlation with Coronal Mass Ejections (CMEs) (Chen, 2011). Also, solar flares are an open area of study not only for the Sun, but also for other stars as well (Haisch, Strong, and Rodono, 1991).

This project is organized as follows; in section 1.1 we give a brief introduction to the Sun and solar magnetic fields and general ideas of flares in section 1.2. Thus, we overview the magnetic changes during flares and point out some questions open on the relation between the vector magnetic field and flares in section 2. Following this approach, in section 3 we present the principal scientific problem of this master thesis and its objectives. Finally in section 4 are summarized the methodology and the timetable to develop this project.

1.1 Sun

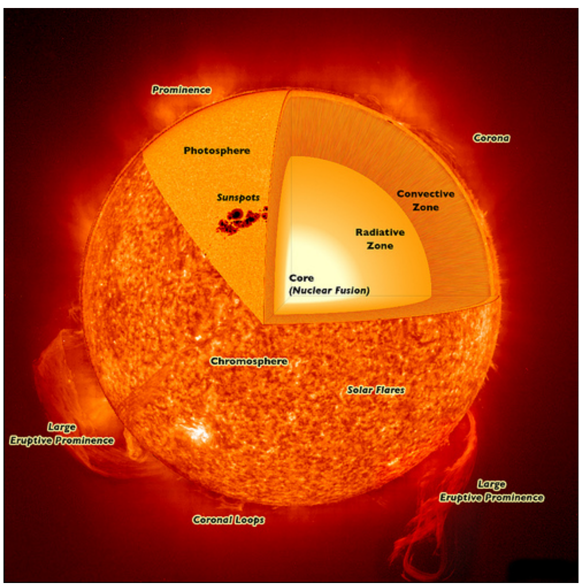

Figure 1: Sketch of Solar structue

The Sun and its strong relation with the life on Earth have interested the cultures around the world for centuries. Nowadays, solar astronomy is an important field on astrophysical and plasma physics. From the stellar point of view, the Sun is a G2V star meaning that its effective surface temperature is around $\sim$5800 K and it is a star in the main sequence, in other words, the Sun is under hydrodynamic equilibrium. Due to the physical processes that occur on the Sun its spectrum goes from high energies such as γ-rays to radio emission; the Fraunhofer lines are the most important features in the optical spectral window.

A general view of the Sun goes from its inner layers to the heliosphere which exhibits the space weather. The solar interior is divided into layers due to physical parameters or conditions that dominate those plasma volumes. The innermost zone is called *the core* where the entire energy of the Sun is created when fusion of four protons produce Helium, energy and some byproducts mainly through $p-p$ chain. Afterwards, radiation and convection transport the energy until it reaches to the *photosphere*.

The photosphere is considered as the visible "surface" of the Sun. The bottom of the photosphere is defined when the optical depth (τ_λ) at 5000Å is equal to one. Some of the characteristics of this zone are the convective cells, bright points and sunspots which are produced by magnetic lines from the interior of the Sun which inhibit the convection transport, thus decreasing the temperature in these zones. Above the photosphere lies the *chromosphere* which is a layer that is not in thermodynamic equilibrium and shows emission lines such Hα with wavelength 6563Å and calcium H and K lines at 3968Å and 3933Å respectively. A thin layer known as the *transition region* separates the chromosphere and the solar corona. In this region, a huge temperature gradient exist which goes from $\sim 10^3$ to $\sim 10^6$K, while the density decreases two orders of magnitude. The corona is the outer region of the solar atmosphere where highly ionized lines of metal elements are observed, meaning that there exist temperatures of millions of Kelvins. In this region loops can be observed which consist of plasma trapped along the magnetic field lines.

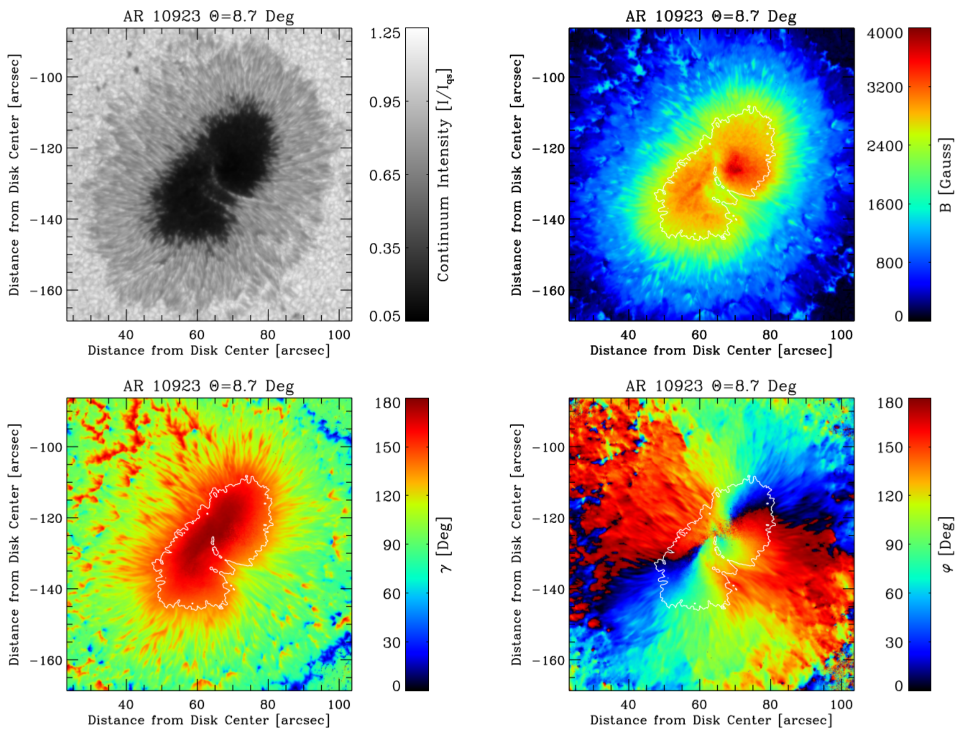

Figure 2: The magnetic field vector in the sunspot AR 10923, November 14, 2006. The upper panels show continuum intensity at 6300Å and the total magnetic field strength. The lower panels display the inclination of the magnetic field vector γ with respect to the observers line-of-sight, and the azimuth of the magnetic field vector in the plane perpendicular to the line-of-sight φ, respectively. Images from Borrero and Ichimoto (2011)

The magnetic fields play an important role in the solar dynamics because many processes are related with them and its changes. Magnetic fields in the Sun are believed to be produced by dynamo processes in the solar interior, and then, its buoyancy against the gravity due to the magnetic pressure that causes the plasma to expand. When magnetic field lines reach the photosphere interact with the medium creating magnetic structures that can be seen over all solar atmosphere in processes such as sunspots and loops in the corona. We can see then, that measuring the magnetic fields of the Sun is a very important to study the solar activity phenomena. Nowadays, the main techniques are based on the Zeeman effect and spectropolarimetry (see figure 2).

1.2 Flares

Solar *flares* are very energetic events occurring in the solar atmosphere. They were first observed in the 19$^{\text{th}}$ century by Carrington (1859) and Hodgson (1859), and since then, this kind of events have been studying widely. Magnetic reconnection is agreed to be responsible to achieve the energy which accelerates particles, and then these particles precipitate into the lower solar atmosphere, heating and moving plasma along the way (Hudson, 2011). The flare process can be thought as a sequence of phases (see figure 3). During the *pre-flare phase* the flare process starts when the solar atmosphere is perturbed by some phenomena such as the growth of loops that collide due to the magnetic pressure between them, a sympathetic flare in other part of the Sun, or some reorganizing turbulent processes. These perturbed conditions shoot the reconnection process where the magnetic field release flare energy. The next stage of the flare process is the *impulsive phase*, at the time of major energy release and when X-ray footpoint sources at chromospheric altitudes are observed. During the *flash phase* the intensity of Hα and its line width rapid increase. Finally, during the *decay phase* we observe meter wave radio bursts and interplanetary particle events due to ejections and shock waves and the coronal plasma returns slowly to its stable state of minimum energy.

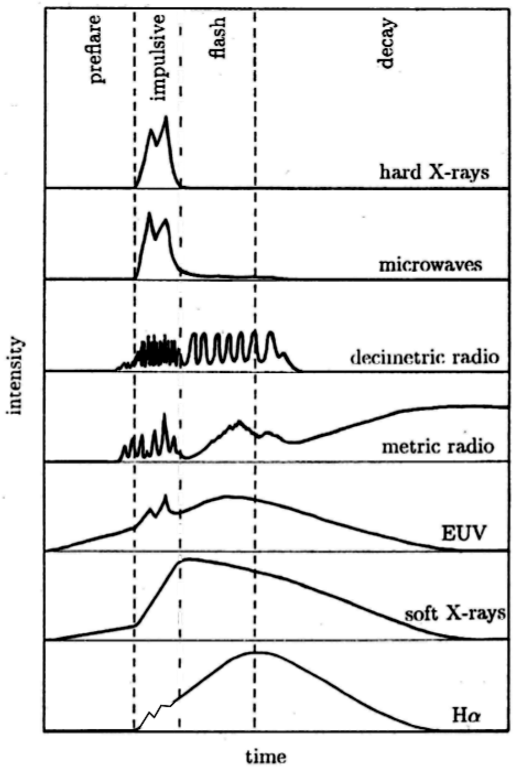

Figure 3: Sketch of the emisions in different bands during a flares (Benz, 2008)

2 State of the Art

The standard model of solar flares takes the magnetic reconnection as the principal mechanism to release the energy. Typical values of the energy release during flares are $\sim 10^{32}$erg and that occur in a volume of $\sim 10^{30}$cm, thus the resulting energy density is $\mathcal{U}_{flare} \sim 100\frac{\text{erg}}{\text{cm}^3}$. Energy densities from possible contributions of different types sources are: kinetic ($\mathcal{U}_{kinetic} \sim 10^{-3}\frac{\text{erg}}{\text{cm}^3}$), thermal ($\mathcal{U}_{thermal} \sim 10^{-1}\frac{\text{erg}}{\text{cm}^3}$), gravitational ($\mathcal{U}_{gravitation} \sim 4 \times 10^{-1}\frac{\text{erg}}{\text{cm}^3}$) and magnetic ($\mathcal{U}_{magnetic} \sim 400\frac{\text{erg}}{\text{cm}^3}$). Then, the physical processes able to store enough energy to produce flares are the coronal magnetic fields. Moreover, soft X-ray images define solar flares as coronal structures. The plasma beta is defined as

$$\beta = \frac{\text{Thermal Presure}}{\text{Magnetic presure}} = \frac{2\xi n_e k_B T_e}{B^2/8\pi}, \tag{1}$$

where ξ is an ionization parameter. When beta is low the plasma is in the magnetically confined regime. On the most parts of the corona $\beta < 1$ (Aschwanden, 2005) letting coronal structures such as loops clearly be defined by the magnetic field and suggesting a strong correlation between flares and the magnetic field.

Observations have shown abrupt and persistent changes in the magnetic field during solar flares in time-scales of minutes (e.g.Sudol and Harvey (2005); Petrie and Sudol (2010); Kosovichev and Zharkova (2001)). Although these magnetic characteristics of flares, one of the basic assumptions in models is that the photospheric magnetic field does not change significantly during flares (Sudol and Harvey, 2005; Priest and Forbes, 2002). Hereafter in this section, we are going to present some results of previous studies of the behaviour of photospheric magnetic fields that give us the opportunity to justify the importance of an statistical analysis of vector magnetic changes during flares.

Sudol and Harvey (2005), and Petrie and Sudol (2010) presented an analysis of solar flares using the magnetic fields along the line-of-sight with GONG data measured on the Ni I line at 676.8 nm. To calculate the changes in the longitudinal magnetic field (B_{los}), they fitted to the light-curves the function

$$B_l(t) = a + bt + c\left\{1 + \frac{2}{\pi}\tan^{-1}[n(t - t_0)]\right\} \quad (2)$$

where t represents time, a and b model the background field evolution, c represents the half-amplitude of the field change, t_0 represents the midpoint of the field change, and n is the inverse of the timescale over which the field change occurs. They found that the step-like field changes are permanent in so far as they persist until the end of the time series which were chosen 2 hours before and after the GOES start time. Also, they presented a correlation between the heliographic locations of the flares and their changes of B_{los} where they clearly saw strong-field changes occur preferentially closer to the limb than to disk center. They explained those changes in terms of geometry, as the line-of-sight (los) direction is nearly horizontal close to the limb, but they could not conclude changes in inclination, because their measurements did not have the information of the full components of the magnetic field.

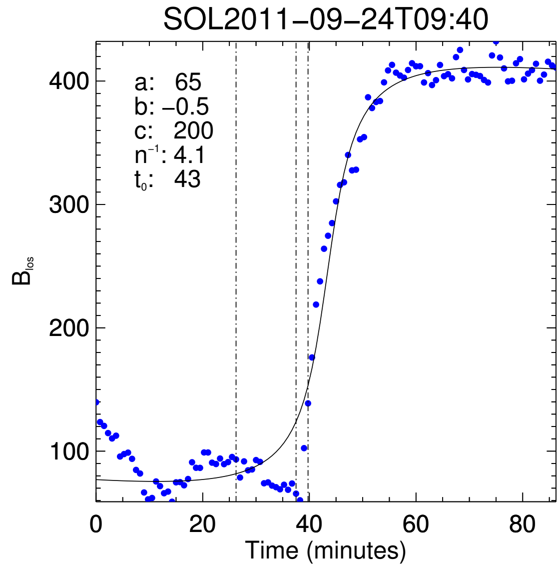

Figure 4: Example of a photospheric magnetic change during `SOL2011-09-24T09:40` flare using the B_{los} data from the HMI instrument on board the SDO satellite. The line is the best fit to the function on equation (2), where the legend show the result parameters. Dotted-dash lines show the start, peak and end GOES times respectily.

Estimating the Lorentz force applied to the photosphere by the coronal field using the photospheric magnetic field measurements under the McClymont model, Sudol and Harvey (2005) calculated how much of the released flare energy goes into reorganizing the photospheric field assuming that the photosphere was in force-balanced equilibrium before the flare. Then, the force imbalance whose vertical component would be

$$\delta f_z = (B_z \delta B_z - B_x \delta B_x - B_y \delta B_y)/4\pi. \quad (3)$$

Petrie and Sudol (2010) found evidences that force changes are more associated with decreases than increases in the longitudinal field, which is consistent with forces of 10^{22} dynes being preferentially directed toward rather than away from the Sun. These results are consistent with the picture of photospheric fields becoming more tilted during flares and may be important in the generation of seismic waves.

Cliver, Petrie, and Ling (2012) studied the magnetic field changes and their relations with the impulsive phase. The authors found consistent results with the big flare syndrome, because nine flares of their sample show less energetic magnetic flux steps than the 66 events that exhibited stepwise changes (mean peak SXR class of M9.9 versus X2.0). In addition, they explained that the onset of the impulsive phase obtained by taking the derivative of the SXR emission is in general agreement with the rapid rise of RHESSI > 100 keV emission, and there is a temporal correspondence of the stepwise change in the unsigned flux and the flare impulsive phase. Then, they concluded that abrupt longitudinal magnetic field changes in the photosphere are a phenomenon of the flare impulsive phase. Because only the line-of-sight component was measured, the change can be either positive or negative, and cannot give any information about the energy contained in the field.

Kosovichev and Zharkova (2001) reported rapid variations of the magnetic field in the lower solar atmosphere during the "Bastille Day Flare", which were irreversible, occurred in the vicinity of magnetic neutral lines, and in a large area of 50Mm^2 at the beginning of the flare. In this event, These authors found two types of magnetic variations: irreversible and transient. They explained that the irreversible changes of $\langle B^2 \rangle$ (or the magnetic energy density) provide evidence of magnetic energy release because $\langle B^2 \rangle$ became permanently lower during the impulsive phase.

In some of the subregions that Kosovichev and Zharkova (2001) studied fields that were pushed toward each other before the flare, probably by external flows. This resulted in an increase of the magnetic field gradient and hence stronger electric currents before the flare, as they suggested. Moreover, they measured movements of the neutral line southward with a speed of $200\ m\ s^{-1}$. Above the neutral line in the area of the positive magnetic polarity the magnetic energy changed significantly less and even increased in a small area, then, they argued that this demonstrates the complexity of the electrodynamic flare processes near the neutral line, which is not well understood. They continued stating that one can imagine a variety of reasons for the apparent asymmetry in the variation of the two polarities. For instance, this might be consistent with the line-of-sight view of shrinkage of magnetic lines connecting the opposite polarities, which may be associated with a reconnection process.

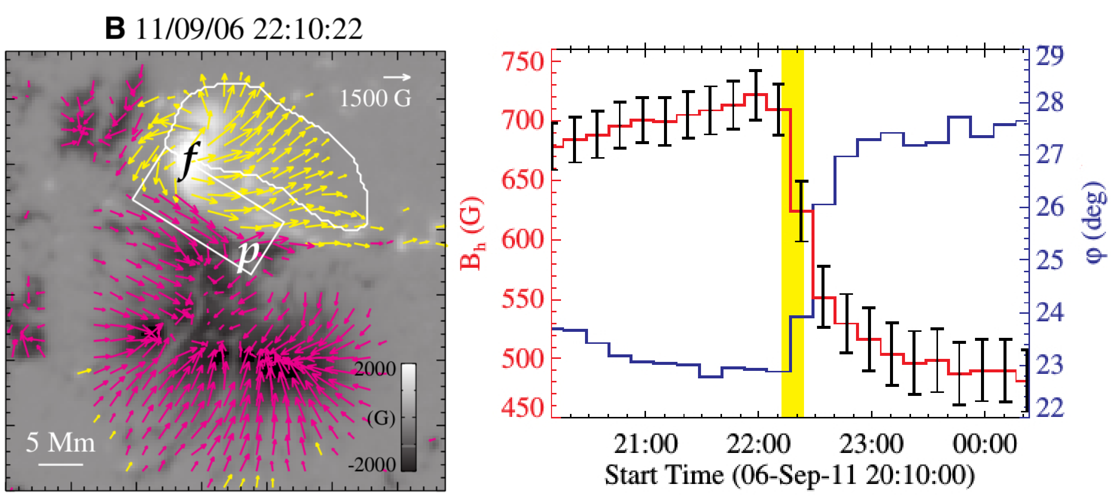

Figure 5: Left panel shows vector magnetic field before the X-class flare occurred on September 6, 2011. The right panel shows the mean temporal evolution of the longitudinal magnetic field and its inclination φ. Futher information can be found in Liu *et al.* (2014).

Wang *et al.* (1994) presented transverse and longitudinal magnetic field measurements bracketing five X-class flares. The data used were obtained with the videomagnetograph system of the Big Bear Solar Observatory (BBSO) and Huairou Solar Observing Station (HSO). These instruments had a typical spatial resolution of 1"-2" and with an aperiodic cadence of tree minutes. Wang *et al.* (1994) measured the shear angle $\Delta\phi$ which is the angular difference between the measured transverse field and the transverse component of the calculated potential field. The weighted magnetic shear S' is given by

$$S' = \frac{\sum |B_t| \Delta\phi}{\sum |B_t|} \tag{4}$$

where the sum are over all pixels in a region centered on the flare. Based on these calculations, Wang *et al.* (1994) found an abrupt increase in the magnetic shear coincident with the X-ray emission during the X3 flare which occurred on August 27, 1990. Meanwhile, the magnetic shear remained at an elevated level after the end of X-ray emission. In another X-class flare they found also changes in the shear before and after the event with values of $S_{before} = 37^o$ and $S_{after} = 75^o$, respectively.

In a recent study of the two homologous X-class flares that occurred on September 6 2011, Liu *et al.* (2014) presented a full 3D reconstruction of the magnetic field including the extrapolation of coronal magnetic fields using the nonlinear force-free field (NLFFF) approach and heliosismic response. In their analysis, they used the vector magnetic observations from the Helioseismic and Magnetic Imager instrument finding variations in the longitudinal component and in its inclination angle (see figure 5). Liu *et al.* (2014) concluded that their model and observations are coherent with the picture of implosions in the low corona. In this idea, the central field collapses toward the photosphere while the peripheral field turns to a more vertical configuration.

2.1 Stokes parameters and the Inversion codes

Any polarization state such as linear, circular, elliptical or natural light of an electromagnetic wave (light beam) can be described by four constants which are certain function of the intensities of the streams. These constants are known as *Stokes parameters* and described the total intensity of the light (I), the linear polarization (Q y U) and the circular polatizarion (V). The I, Q, U and V can be measured with a combination of a linear analyzer-polarizer plus a linear retarder. Images of the four Stokes parameters of a sunspot observed on January 29, 2007 are in figure 6.

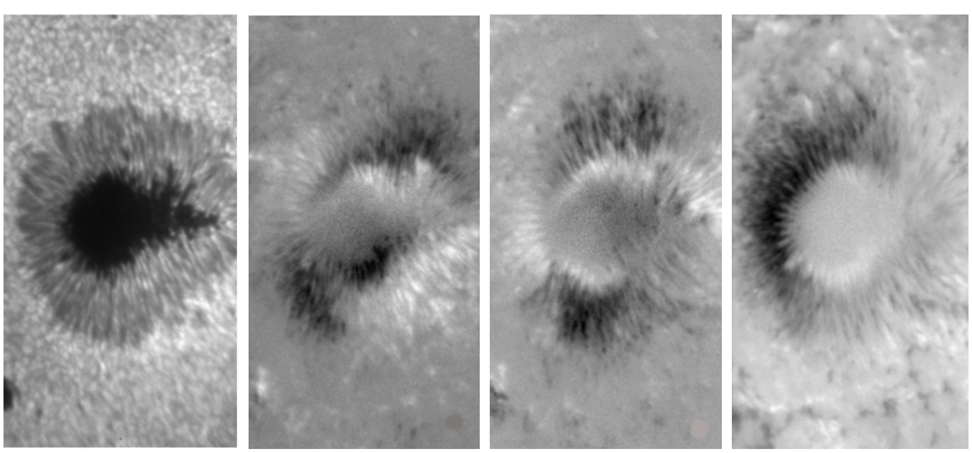

Figure 6: Sunspot images of the four Stokes parameters I, U/I, Q/I, V/I at the absorption line Fe 6302Å January 29, 2007. Images were taken from Kleint (2006)

The Helioseismic and Magnetic Imager (HMI) on board the SDO satellite measures the solar magnetic fields using the polarization states of the sunlight. This instrument is able to take the four Stokes parameters I, Q, U, V, using 6 narrowband filters along the Fe I absorption line at 6173Å. With these four parameters and solving the radiative transfer equation in a magnetized medium, the inversion codes are able to retrieve the full magnetic field vector. To do the inversion procedure we are going to use the Very Fast Inversion of the Stokes Vector for the Helioseismic and Magnetic Imager (VFISV) by Borrero *et al.* (2011). This code works with 11 parameters of atmosphere model $\mathcal{M}$ to make a synthetic profile of the four Stokes parameters. Then, it compares the obtained synthetic profile with the observational one using a χ^2 procedure as:

$$\chi^2 = \frac{1}{4L - F} \sum_{i=1}^{L} \sum_{j=i}^{4} \left[I_j^{obs}(\lambda_i) - I_j^{syn}(\lambda_i, \mathcal{M}) \right]^2 \frac{\omega_{ij}^2}{\sigma_i^2} \tag{5}$$

where $4L - F$ refers to the free parameters of the inversion and σ_i and ω_{ij} are the noise level and weight function of the Stokes parameters. The code uses the Levenberg-Marquardt algorithm to minimize the χ^2 and in the end one obtains the strength B, inclination with respect to the observer γ and azimuth φ of the magnetic field vector.

3 Objectives

To better understand flare processes, it is necessary to investigate the structure and changes of the magnetic field in the solar atmosphere. In addition, during the works cited before statistical analysis of vector magnetic fields during flares could not be done because the instruments and observing conditions. Nowadays, high cadence data from satellites give us the opportunity to study flares with high temporal and spatial resolution and a full 24 hours coverage. The Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamic Observatory (SDO) produces observations of photospheric intensity, velocity, and magnetic field. This new generation of data open the doors to statistical analysis in the vector magnetic fields during flares.

The principal objective of this Master thesis is:

Create large statistics of flare-related changes and especially to investigate the vector magnetic field, which allows us to determine how the 3D magnetic field rearranges during flares.

Specific objectives of this work are:

- Develop computational tools to perform the data reduction of satellite data and its analysis.
- Calculate physical quantities from vectograms such the work done by the magnetic field and the change in the Lorentz force.
- Quantify the type of magnetic changes as a full vector and its components, their location over the Active Region and heliographic position.
- Compare the observational results with the Standard Model of solar flares.

4 Methodology and Timetable

This project is planned to be carried out in one year starting from January 2015 and ending on December 2015 with the final dissertation document. The methodology for this work is based in two branches. The first one is the acquisition of the knowledge in the Solar Astronomy, flare processes, radiation mechanisms, solar magnetic fields, the standard model of flares and all related areas necessary to understand the physical processes during explosive events on the solar atmosphere. To synthesise this work, we are going to have weekly seminars to present the advances. The second part of methodology is related to observational work, i.e., the reduction and analysis of satellite data. To summarize this methodology timetable (1) shows a monthly description of the activities to be done during the master.

Activity	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
References revision & academic seminars												
Analysis of initial sample												
Choosing the final events sample												
Obtain the vector magnetic field data												
Develop of reduction data procedures												
Develop analysis tools												
Analyze of satellite data and contrast it with flare models												
Write the dissertation document												

Table 1: Timetable of the activities during the Master to develop the project

References

Alvarado-Gómez, J.D., Buitrago-Casas, J.C., Martínez-Oliveros, J.C., Lindsey, C., Hudson, H., Calvo-Mozo, B.: 2012, Magneto-Acoustic Energetics Study of the Seismically Active Flare of 15 February 2011. Sol. Phys. **280**, 335 – 345. doi:10.1007/s11207-012-0009-6.

Aschwanden, M.J.: 2005, *Physics of the Solar Corona. An Introduction with Problems and Solutions (2nd edition).*

Benz, A.O.: 2008, Flare Observations. *Living Reviews in Solar Physics* **5**, 1. doi:10.12942/lrsp-2008-1.

Borrero, J.M., Ichimoto, K.: 2011, Magnetic Structure of Sunspots. *Living Reviews in Solar Physics* **8**, 4. doi:10.12942/lrsp-2011-4.

Borrero, J.M., Tomczyk, S., Kubo, M., Socas-Navarro, H., Schou, J., Couvidat, S., Bogart, R.: 2011, VFISV: Very Fast Inversion of the Stokes Vector for the Helioseismic and Magnetic Imager. Sol. Phys. **273**, 267 – 293. doi:10.1007/s11207-010-9515-6.

Carrington, R.C.: 1859, Description of a Singular Appearance seen in the Sun on September 1, 1859. MNRAS **20**, 13 – 15.

Chen, P.F.: 2011, Coronal mass ejections: Models and their observational basis. *Living Reviews in Solar Physics* **8**(1). doi:10.12942/lrsp-2011-1. http://www.livingreviews.org/lrsp-2011-1.

Cliver, E.W., Petrie, G.J.D., Ling, A.G.: 2012, Abrupt Changes of the Photospheric Magnetic Field in Active Regions and the Impulsive Phase of Solar Flares. ApJ **756**, 144. doi:10.1088/0004-637X/756/2/144.

Haisch, B., Strong, K.T., Rodono, M.: 1991, Flares on the sun and other stars. ARA&A **29**, 275 – 324. doi:10.1146/annurev.aa.29.090191.001423.

Hodgson, R.: 1859, On a curious Appearance seen in the Sun. MNRAS **20**, 15 – 16.

Hudson, H.S.: 2011, Global Properties of Solar Flares. Space Sci. Rev. **158**, 5 – 41. doi:10.1007/s11214-010-9721-4.

Kleint, L.: 2006, Spectropolarimetry of the chromosphere with ibis. Master's thesis, Eidgenössische Technische Hochschule Zürich. ETH.

Kosovichev, A.G., Zharkova, V.V.: 1998, X-ray flare sparks quake inside Sun. Nature **393**, 317 – 318. doi:10.1038/30629.

Kosovichev, A.G., Zharkova, V.V.: 2001, Magnetic Energy Release and Transients in the Solar Flare of 2000 July 14. ApJL **550**, 105 – 108. doi:10.1086/319484.

Liu, C., Deng, N., Lee, J., Wiegelmann, T., Jiang, C., Dennis, B.R., Su, Y., Donea, A., Wang, H.: 2014, Three-dimensional Magnetic Restructuring in Two Homologous Solar Flares in the Seismically Active NOAA AR 11283. ApJ **795**, 128. doi:10.1088/0004-637X/795/2/128.

Petrie, G.J.D., Sudol, J.J.: 2010, Abrupt Longitudinal Magnetic Field Changes in Flaring Active Regions. ApJ **724**, 1218 – 1237. doi:10.1088/0004-637X/724/2/1218.

Priest, E.R., Forbes, T.G.: 2002, The magnetic nature of solar flares. A&A Rev. **10**, 313 – 377. doi:10.1007/s001590100013.

Shibata, K., Magara, T.: 2011, Solar Flares: Magnetohydrodynamic Processes. *Living Reviews in Solar Physics* **8**, 6. doi:10.12942/lrsp-2011-6.

Sudol, J.J., Harvey, J.W.: 2005, Longitudinal Magnetic Field Changes Accompanying Solar Flares. ApJ **635**, 647 – 658. doi:10.1086/497361.

Wang, H., Ewell, M.W. Jr., Zirin, H., Ai, G.: 1994, Vector magnetic field changes associated with X-class flares. ApJ **424**, 436 – 443. doi:10.1086/173901.