Solar flare and its interaction with the Earth atmosphere: An Introduction

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Abstract

Solar flare is a diverse dynamic activity of solar atmosphere. It is associated with high magnetic energy release (10^{27}J), particle acceleration, radiation burst and release of plasma particles into the space. In this paper we studied the different aspects of solar flare such as magnetic reconnection, radiation burst, magneto hydrodynamic, and interaction with Earth atmosphere from the fundamental point of view.

1. Introduction

Sun is a main sequence G2 spectral class star of the universe and full of mysterious activity like Sun Spots, Solar Cycles, Solar Flare, CME, Solar Prominences etc. Sun is a gaseous ball of plasma and continuously emitting radiations. The total solar radiation of the entire Sun is 3.83 X 10^{23} kW [1]. Sun is a magnetic active star [2] and mostly activity is due to the variation in magnetic field. Solar magnetic field is generated in the convection zone by a dynamo process which is a combination of solar rotation and convection [3]. The magnetic field of various activity of Sun are depicted in table 1[1]. According to solar standard model [4], Sun structure is considered as an internal as well as external structure (solar atmosphere). Solar atmosphere comprises photosphere, chromospheres and corona. The basic temperature and density parameters of Sun structure are depicted in table 2 [1].

Solar flare is an solar atmospheric activity and first discovered or observed by R. C. Carrington and R. Hodgman on 1st September 1859 independently in optical light [5][6]. Solar Flare is associated with solar spots (high magnetic field, ~3000 Gauss), solar cycle (variation in number of sun spots in 11 year) and sometime by coronal mass ejections (plasma particles propagation along with magnetic field lines). Solar Flare is an intense variation of energy into solar corona. Though, Sun is continuously emitting energy in the form of radiation in all wavelengths from radio to gamma rays (please see Appendix A for wavelengths, frequency and energy of electromagnetic radiation spectrum) but during flare an intense increase arise in the radiation level of the Sun [7]. Also huge amount of plasma particles accelerate in the space along with magnetic field lines say CME (sometimes), solar wind etc.

It is widely believed that flares are caused by the release of magnetic energy up to some 10^{27} J in the solar atmosphere within a relatively short time between 100 and 1000 s. Release of magnetic energy causes particle acceleration (electrons, protons, and heavier particles) and turbulence in solar atmosphere. This energy accelerates particles to tens and hundreds of keV. Electrons accelerated to 10-100 keV can contain a significant fraction (10-50%) of this energy. The accelerated particle causes intense radiations in all wavelengths. Inside the solar flare, gas temperature can reach up to 10 or 20 million degrees Kelvin. It can be as high as 100 million degrees Kelvin.

It is observed that there are typically three stages in a solar flare [8]. First is the precursor stage, where the release of magnetic energy is triggered. Soft X-ray emission is detected in this stage. In the second or *i*mpulsive stage, protons and electrons are accelerated to energies exceeding 1 MeV. During the impulsive stage, radio waves, hard X-rays, and gamma rays are emitted. The gradual build up and decay of soft X-rays can be detected in the third, decay stage. The duration of these stages can be as short as a few seconds or as long as an hour**.**

Solar flares are mainly categorized in single loop and two ribbon flares. Single loop flares are single magnetic loop or flux tube brightens in X-rays and remains apparently unchanged in shape and position throughout the event. Two ribbon flares are much larger than a compact flare and takes place near a Solar prominence, a loop of plasma confined between two magnetic field lines [9]. The Hα and Soft X-ray classification scheme is given in appendix A. A B C M and X class classification depend upon peak flux. The X-class flare denotes the most intense flares, while the number provides more information about its strength. An X2 is twice as intense as an X1, an X3 is three times as intense, etc.

In the present time, solar flares are observed in all wavelengths from radio to gamma rays emissions excess in to 10 MeV. Space based observatories and Ground based observatories are in use for observing solar flare. YOHKOH, GOES, RHESSI, SDO, SOHO, WIND was/are the major solar space observatories [10]. An example of solar flare observed by SOHO spacecraft is shown in figure 1. A flare observed by the GOES satellite based on the X-ray radiation level of Sun is shown in figure 2.

In this paper we studied introductory aspects of solar flare, magnetic reconnection, magneto hydrodynamic, radiative process and its interactions with the Earth atmosphere.

Table 1: Magnetic field of different activities on Sun

Solar Activity	**Magnetic Field (Gauss)**
Polar Field	1-2
Sun Spots	3000
Promineces	10-100
Chromospheric plages	200
Bright chromospheric network	25
Ephemeral (unipolar) active regions	20

Table 2: Temperature and density parameters of Sun Structures

Solar Structure	**Temperature (K)**	**Density (Kg/m3)**
Interior (centre of Sun)	15 000 000 K	16000
Surface (photosphere	6050 K	10^{-6} kg/m3
Sunspot umbra (typical)	4240 K	
Sun spot Penumbra (typical)	5680 K	

Chromospheres	4300 to 50 000 K	10^{-9} kg/m3
Corona	800 000 to 3 000 000 K	10^{-13} kg/m3

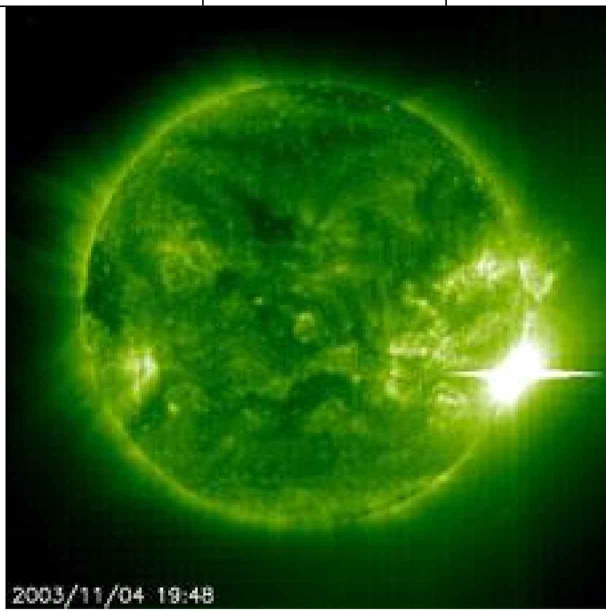

Figure 1: The Sun unleashed a powerful flare on 4 November 2003. The Extreme ultraviolet Imager in the 195A emission line aboard the SOHO spacecraft captured the event. **Credit:** SOHO, ESA & NASA

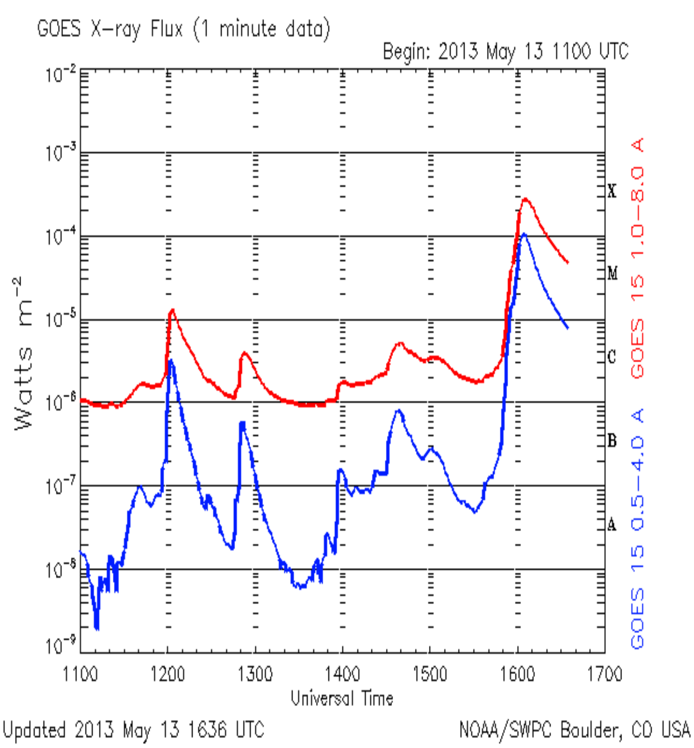

Figure 2: X-ray flux from the Sun of 13.05.2013 (GOES-15), Image courtesy: NASA

2. Magnetic Reconnection

Magnetic reconnection is a natural process of plasma state of the matter. Magnetic reconnection is a process where magnetic field lines are broken and rejoined in highly conducting plasma. Solar flare is caused by magnetic reconnection. During solar flare magnetic reconnection will dissipate magnetic energy which will cause particle acceleration and release of huge amount of emissions. The process of magnetic reconnection was first postulated by Giovanelli (1946) [11].

The term magnetic reconnection was first proposed by Dungi in 1953[12]. Dungy suggested the formation of current sheet within the perspective of magneto hydrodynamics. In the current sheet the magnetic field will reconnected and diffusion occurs. The differential rotation of Sun, solar dynamo, and convection ensure that the magnetic field of the Sun is typically highly stressed and prone to reconnection events [13]. Here we presented cartoons for solar flare formation taking magnetic reconnection as a process. It is shown in figure 3 a, 3b, 3c and 3d respectively. The figures are not in scale.

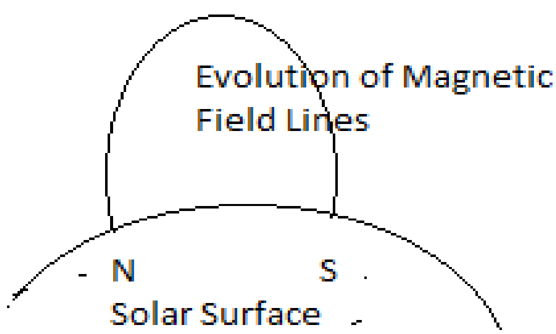

Figure 3a: Evolution of magnetic field lines

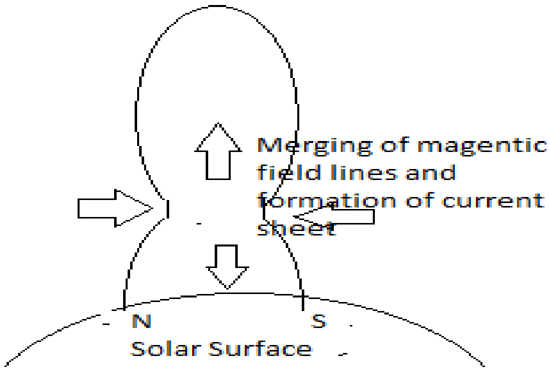

Figure 3b: Twisting of magnetic field lines and current sheet formation

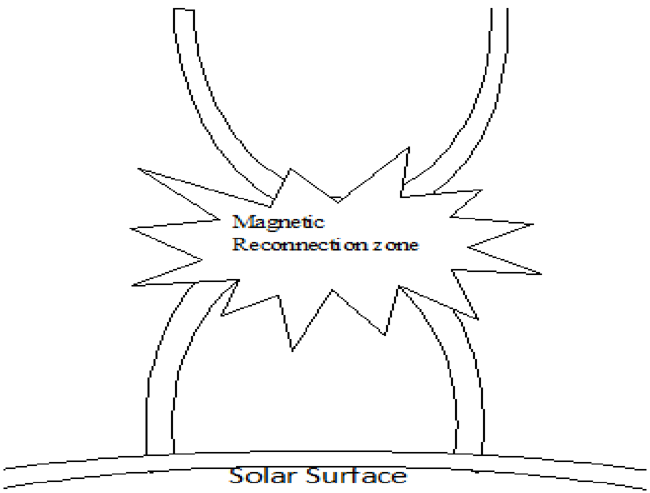

Figure 3c: Release of magnetic Energy

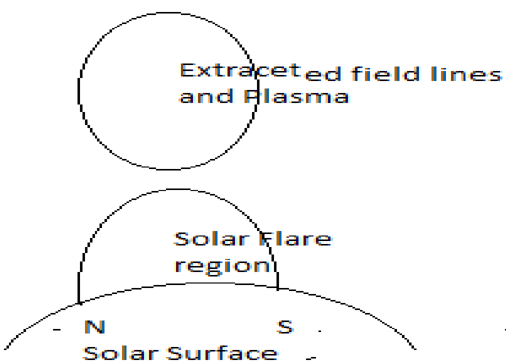

Figure 3d: Solar flare formation and extraction of field lines

After the postulation of magnetic reconnection several models have been proposed. The first model to describe magnetic reconnection was developed by Parker (1957) and Sweet (1958) [14] [15] in terms of enhanced magnetic diffusion in a layer with anti parallel field lines on both sides. This model found slow at time scale in solar flare conditions. Later Petschek [16] develop fast reconnection model considering small current sheet. A schematic of Sweet Parker and Petschek models of Reconnection is shown in figure 4

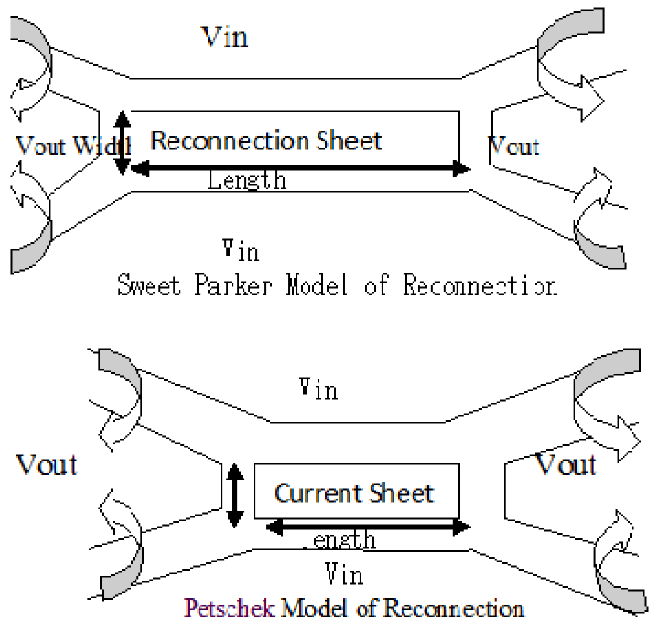

Figure 4: Sweet-Parker and Petschek Model of magnetic reconnection (figures are not in scale)

Under steady state conditions Sweet parker calculated the rate of flow of plasma from the current sheet. If E_y is the uniform out of plane electric field and B_{in} is the magnetic field of reconnection region, than;

$$E_y \sim V_{in} B_{in}$$

According to Appere's law, the current density is given by;

$$J_y \sim \frac{B_{in}}{\mu_o \delta}$$

Where δ is the half thickness of Sweet parker model thickness. A relation resistivity η, in flow velocity V_{in} and current sheet half thickness δ will be equal to;

$$V_{in} \sim \frac{\eta}{\mu_o \delta}$$

The above relationship represents the condition that the resistive electric field, ηJy, within the current sheet matches the ideal electric field outside the current sheet. The thickness of a steady state reconnection layer is set by how quickly magnetic field lines can diffuse.

Conservation of mass will give a relationship under incompressible conditions;

$$V_{in} L \sim V_{out} \delta$$

Where L is the half thickness of the reconnection layer and Vout is the outflow velocity. According to the conservation law of energy;

$$V_{in} L \left(\frac{B^2{}_{in}}{2\mu_0} \right) \sim V_{out} \delta \left(\frac{\rho V^2{}_{out}}{2} \right)$$

Solving this equation we will get following relationship

$$V_{out} \sim V_A \equiv \frac{B_{in}}{\sqrt{\mu_0 \rho}}$$

Thus out flow velocity in a Sweet Parker current sheet scales with the upstream Alfen speed. The dimension less reconnection rate ca be given by

$$\frac{V_{in}}{V_A} \sim \frac{1}{\sqrt{S}}$$

Where S is the Lundquist number and is equal to;

$$S = \frac{\mu_0 L V_A}{\eta}$$

Sweet Parker model is not able to explain the extremely short time scales of seconds to minutes observed for energy release during solar flare. Sweet Parker is found correct for the resistive MHD framework for moderate Lundquist number ($S \sim 10^2 - 10^4$).

The second most important model was proposed by Petschek (1964)[16] as shown in figure 4. Petschek modify Sweet parker model considering small current sheet. Perschek considered that diffusion region must be small than the global length scale. He proposed a mechanism for the diffusion in a smaller length scale considering slow mode shocks. The maximum reconnection rate is given by

$$\frac{V_{in}}{V_{out}} \approx \frac{\pi}{8 \ln S}$$

In the beginning, the Petschek model got good acceptance but it is found that under resistive MHD conditions only Sweet Parker type current sheet will form as studied by Biskamap in 1986 [17]. Experimental and observational results ruled out the formation of Petschek current sheet.

Apart from these two models several other models are also given by researchers such as Turbulent Reconnection, Two Fluid Reconnection, Asymmetric Reconnection etc.[18].

Multiple wavelength observations by modern satellites strongly suggest that magnetic reconnection is the principal process for the energy conversion in solar flares. Typical cusp-like feature of post-flare loops observed in soft X-rays is a strong piece of evidence in favour of the reconnection model [19].

The solar flare standard model [20] is known as CSHKP model. This model was developed by pioneer researchers Carmichael (1964), Sturrock (1966), Hirayama (1974), and Kopp-Pneuman (1976). Kopp and Pneuman (1976) considered that after reconnection of open field line, the solar wind along open field line collides to form shock inside the reconnected closed field, which heat the coronal plasma to are temperature. However, Cargill and Priest (1982) correctly pointed out that we should consider the role of slow mode shock associated with Petschek type reconnection. Forbes and Priest (1984) noted the formation of fast shock (termination shock) due to reconnection jet above the reconnected loop, and Forbes and Malherbe (1986) pointed out that the slow shock is dissociated to isothermal slow shock and conduction front in solar are condition.

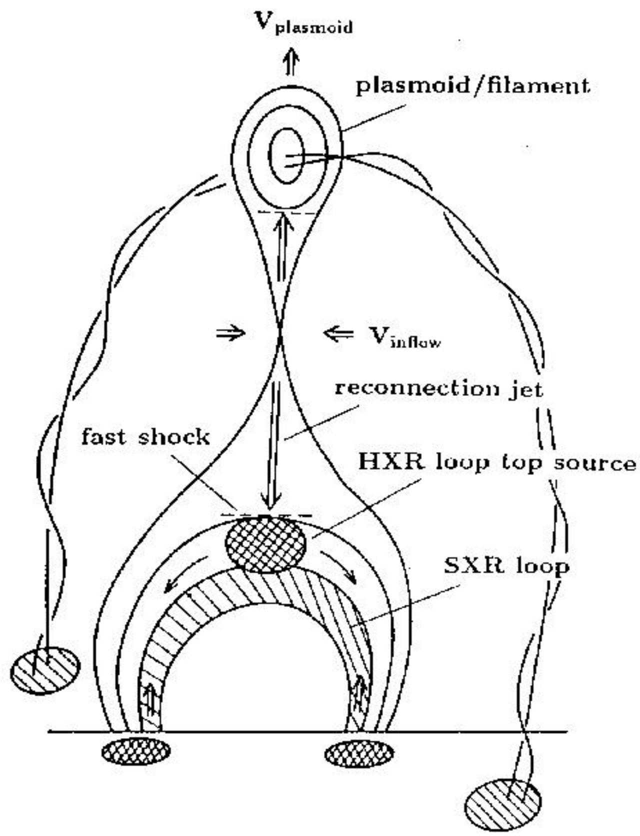

Figure 5: A standard model of solar flare as developed by Shibata

Some of the solar flares parameters observed and derived from the theoretical modeling are summarized in table 3[7] [13].

Table 3: Physical parameters of the Solar Flare

Flare Properties	**Values**
Flare Energy	10^{27} J
Flare Temperature	10^{7} K
Flare Volume	$(10^{4}\ \text{km})^{3}$
Fare Loop Height	10^{4} to 10^{5} Km
Plasma Density	$10^{10}\ \text{cm}^{-3}$
Duration of flare (time scale)	$10^{3} – 10^{4}$ s
Electron energies	>10 MeV
Proton energies	>100 MeV
Number of energetic electrons	10^{36} per second

3. Magneto hydrodynamics of the Flare

Magneto hydrodynamic is a dynamics of plasma material in the influence of magnetic field. Magneto hydrodynamics is similar to fluid dynamics. Magneto hydrodynamic equation, relates different parameters of plasma, are used for studying dynamics of plasma. The solutions of MHD equations provide detail information about the plasma flow. Analytical and Numerical methods are used for solving magneto hydrodynamic equations.

MHD equations are non-linear partial differential equations. The basic Magneto hydrodynamic equations [21] are as follows:

Mass conservation equations;

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho V) = 0$$

Momentum conservation equation;

$$\rho \frac{\partial V}{\partial t} + \rho (V.\nabla) V = -\nabla p + \tfrac{1}{\mu} (\nabla \times B) \times B + \rho g$$

Faraday's equations

$$\frac{\partial B}{\partial t} + (\nabla \times E) = 0$$

Gauss law;

$$\nabla . B = 0$$

Ampere's law;

$$\nabla \times B = \mu j$$

Equation of state;

$$p = \frac{\kappa_B}{m} \rho T$$

Here ρ is mass density, V is flow velocity, B is the magnetic field, E is the electric field, p is gas pressure, $\gamma = 5/3$ is the adiabatic index, g is gravitational acceleration, T is temperature, m is mean particle mass and k_B is the Boltzmann's constant. MHD equations relates plasma unknown parameters with one another.

Induction equation is derived by using Ampere's law and ohm's law,

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) + \eta \nabla^2 B$$

The first term of the right side describes advection and second term diffusion.

A dimension less number, Magnetic Reynold number is defined as a ratio of advection and diffusion terms.

$$R_m = \frac{\nabla \times (v \times B)}{\eta \nabla^2 B}$$

If $R_m >> 1$; advection term will dominate (condition is known as frozen in flux).

If $R_m << 1$; Diffusion term dominate and reconnection occurs.

Plasma beta parameter is defined as a gas pressure (p) to magnetic pressure ($B^2/2\mu$). It is equal to;

$$\beta = \frac{2\mu p}{B^2}$$

If $\beta >> 1$, the gas pressure will dominate (Photosphere of Sun)

If $\beta << 1$, the magnetic pressure will dominate (Solar corona)

Forbes & Priest 1983; Magara et al. 1996; Ugai 1996; Forbes & Malherbe 1991 carried out magneto hydrodynamic simulation on magnetic reconnection models in two dimensions. This simulation work was mainly concentrated to simulate basic geometry of solar flare such as the reconnection site structures with an X-type magnetic neutral point associated with extending slow-mode MHD shocks, bidirectional reconnection jets, fast-mode MHD shock formed at the top of reconnected loops, and upward ejecting plasmoids. These simulations do not include thermal processes such as heat conduction. Forbes and Melherbe ((1991) simulated magnetic reconnection by considering radiative cooling effect.

Yokoyama and Shibata (1997) carried out first time the self-consistent MHD simulation for the reconnection. Yokoyama and Shibata (1998, 2001) [22] [23] performed 2D MHD simulation of reconnection with heat conduction and chromospheres evaporation. This simulation is considered as a most advanced model of eruptive areas.

An illustration of the reconnection model of a solar flare based on the simulation results is shown in figure 6. This model was develop by the simulation study carried out by the Petschek 1964; Tsuneta 1996; Shibata 1996. Thick solid lines show magnetic field. Magnetic energy is released at slow-mode MHD shocks emanating from the neutral X-point, which is formed as a result of the magnetic reconnection. The ejected reconnection jet collides with the reconnected loops and forms a fast-mode MHD shock. The released heat at the reconnection site conducts along the field lines down to the chromospheres. Because of the heat input into the dense chromospheres plasma, the plasma there evaporates and flows back toward the corona.

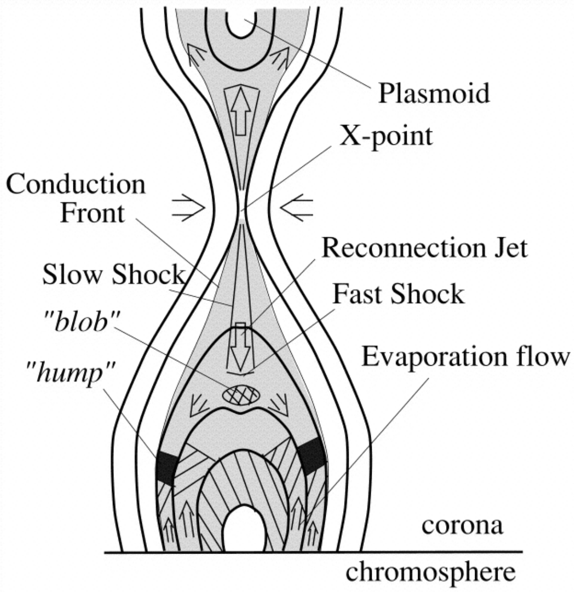

Figure 6: Schematic picture of the model; e.g., Petschek 1964; Tsuneta 1996; Shibata 1996

4. Flare Radiations

Most of information about the astronomical bodies, phenomenons and processes are obtained by studying electromagnetic radiations which comes from the object. Radio, microwave infrared, visible, ultraviolet, X rays, gamma rays are known as electromagnetic radiations. The electromagnetic (EM) spectrum is the range of all types of EM radiation. The wavelength, frequency and energy of electromagnetic radiation are given in the Appendix. The basic properties associated with radiation are luminosity, flux, intensity, emissivity, radiation energy density, Einstein coefficients, mean free path etc. **[24]**

Electromagnetic radiation is produced whenever a charged particle is accelerated. The greater the acceleration the higher the energy of the emitted photon will produce. The basic mechanisms for the production electromagnetic radiations are as follows:

- Bremsstrahlung (free-free emission)
- Compton Scattering
- Synchrotron emission
- Absorption processes
    - Self-absorption
    - Pair production
- Ionisation Losses
- Cherenkov radiation
- Nuclear interactions

There are two types of electromagnetic radiation: thermal radiation - which depends on the temperature of the emitting source - and non-thermal - which does not depend on the source temperature. The thermal radiation processes are black body radiation and thermal bremstrahlung. The Non thermal emissions are non thermal bremstrahlung, inverse Compton scattering and synchrotron radiation

X-ray and radio emission mechanism can also be classified as coherent and incoherent emissions. Coherent emission mechanisms are plasma emission and the electron cyclotron maser mechanisms. Incoherent emission mechanisms include bremsstrahlung and gyro-emission.

In solar flare an intense radiation occurs in all wavelength of electromagnetic spectrum at different Locations of flare regions. Nearly half of energy released during flares is used to accelerate electrons and protons up to velocity nearly speed of light. Solar flares accelerate particles to nearly the velocity of light, hurling them out into the solar system and down into the Sun. Both Thermal and Non thermal radiations occurs in solar flares [26].

X-ray emissions from solar flare provide a detail study of physical properties of Solar flare. X-ray emission can be classified as hard X-ray (10-100KeV) emissions and soft X-ray (~0.1-10 keV) emissions. SXR often refers to the thermal part of the photon bremsstrahlung spectrum, which can go up to 20 keV in powerful flares. Hard X-ray referred as non thermal power law like spectrum. The hard X-rays are widely believed to be non thermal bremsstrahlung emission produced by high-energy electrons precipitating into the chromospheres. High-speed electrons that are thrown down into the Sun emit hard X-rays when entering the lower solar atmosphere [26]. An illustration of X-ray photon production in solar flare is shown in figure 7.

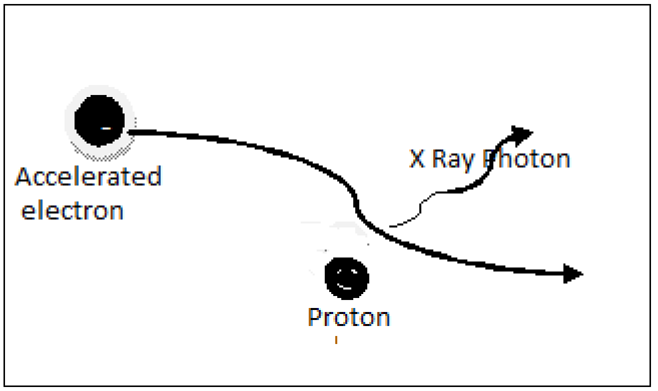

Figure 7: Production of X ray in Solar Flare

Hard X-ray emission and the evolution of high-temperature thermal flare plasma are often referred to as the Neupert effect. Jain, Rajmal, et Al. [27][28][29] studied X ray emissions, observed by SOXS mission of India, from solar flare meticulously and derived many conclusions about Solar flare. According to Jain et. al, [27][28][29] The evolution of the break energy point that separates the thermal and non-thermal processes reveals increase with increasing flare plasma temperature. Jain et al., [27][28][29] also concluded that the X-ray energy spectrum from a typical large solar flare is dominated by soft X-ray line and thermal (free-free) bremsstrahlung emission at $\varepsilon \approx$ 1–20 keV, and collisional bremsstrahlung of non-thermal electrons at $\varepsilon \approx$ 20–1000 keV .

Gamma and neutrons emissions from solar flare provide information about flaring process and conditions within flare loop [30]. Gamma ray emissions are generally associated with most powerful solar flares. Energetic flare protons create nuclear reactions when they are tossed down into the chromosphere or photosphere, emitting gamma rays in the process Solar flare are generally associated with such as the nuclear lines from excited nuclei, as well as the delayed neutron capture line, and the electron-positron annihilation line and continuum.

For gamma rays, protons and heavier ions accelerated in the flare. These high energy particles interact with the nuclei of the different elements in the ambient solar atmosphere to produce a far more complicated emission spectrum than the relatively smooth continuum bremsstrahlung spectrum. Many individual gamma-ray lines from a wide variety of different elements in the solar atmosphere have been detected. They result from the decay of such relatively abundant elements as carbon, nitrogen, oxygen, etc. that are excited to high energy states in the various nuclear interactions. The relative intensities of the various lines provide information about the composition of both the accelerated particles and the target nuclei [31].

5. Earth Atmosphere and Flare Interaction

Earth atmosphere is the protective layers of gases which surrounds the Earth. It receives solar radiation in the form of radiations and plasma particles (CME, solar wind etc) from the Sun. Earth atmosphere mainly constitute nitrogen (78%), oxygen (21%) and other gases. Gravity holds the atmosphere to the Earth's surface. With the height the atmosphere becomes thinner. Earth atmospheres (figure 8) are classified into five layers;

1) The troposphere is the first layer above the surface and contains half of the Earth's atmosphere. Weather occurs in this layer. 2) Many jet aircrafts fly in the stratosphere because it is very stable. Also, the ozone layer absorbs harmful rays from the Sun. Meteors or rock fragments burn up in the mesosphere. 4) The thermosphere is a layer with auroras. It is also where the space shuttle orbits. 5) The atmosphere merges into space in the extremely thin exosphere. This is the upper limit of our atmosphere.

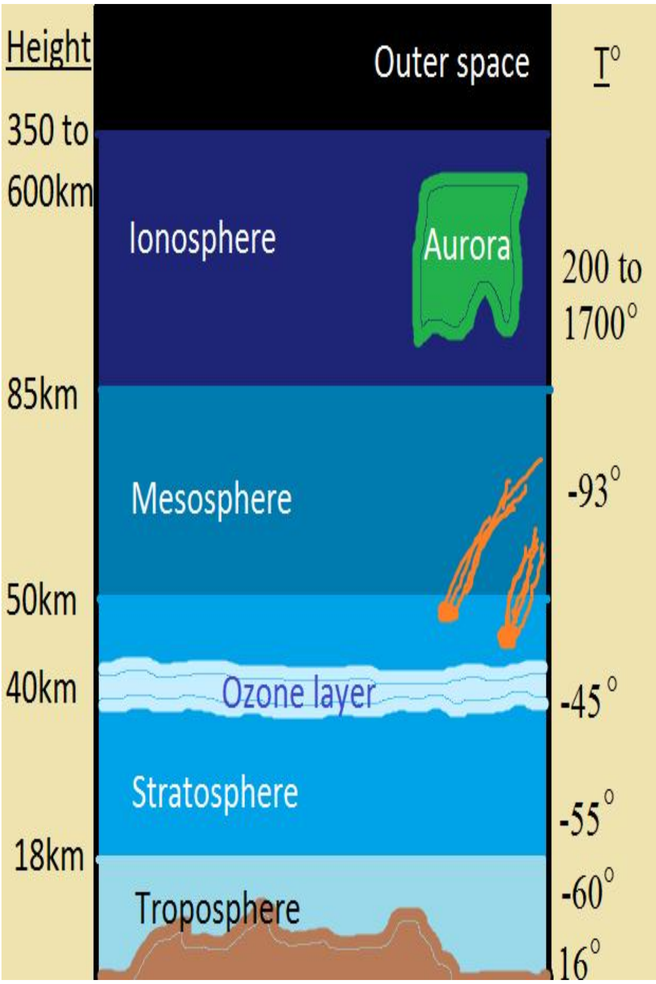

Figure 8: Earth Atmosphere with height

Flare interaction is assumed as an interaction of plasma particles and intense radiation with the Earth atmosphere. The key processes of the interaction take place are the emission, absorption and scattering. As discussed above that Solar flare produces high energy particles (protons, electrons ions etc.) and radiations. The particles are stopped by the magnetic field of earth. Radiation (mainly X ray and UV) is stopped by ionosphere layer of earth atmosphere. As the charged particles of solar winds and flares hit the Earth's magnetic field, they travel along the field lines [32].

A sudden ionosphere disturbance (SID) occurs during flare. The ionosphere starts at about 70-80 km high and continues for 640 km. It contains many ions and free electrons (plasma). The ions are created when sunlight hits atoms and tears off some electrons. Auroras occur in the ionosphere. the ionosphere is composed of three main parts, named for obscure historical reasons: the D, E, and F regions. The electron density is highest in the upper, or F region. The F region exists during both daytime and nighttime. During the day it is ionized by solar radiation, during the night by cosmic rays.

The flare's X-ray energy increases the ionization of all the layers, including the D. Electromagnetic radiation at wavelengths of 100 to 1000 Angstroms (ultraviolet) ionizes the F region, radiation at 10 to 100 Angstroms (soft X-rays) ionizes the E region, and radiation at 1 to 10 Angstroms (hard X- rays) ionizes the D region. When electromagnetic radiation from the sun strips an electron off a neutral constituent in the atmosphere, the resulting electron can spiral along a magnetic field line at the electron gyro frequency.

When a Solar Flare occurs, the VLF propagation is disturbed and it is possible to detect the SIDs by monitoring the variations or the signal level of a distant VLF receiver. Figure 9 is an artistic view of flare interaction with Earth atmosphere.

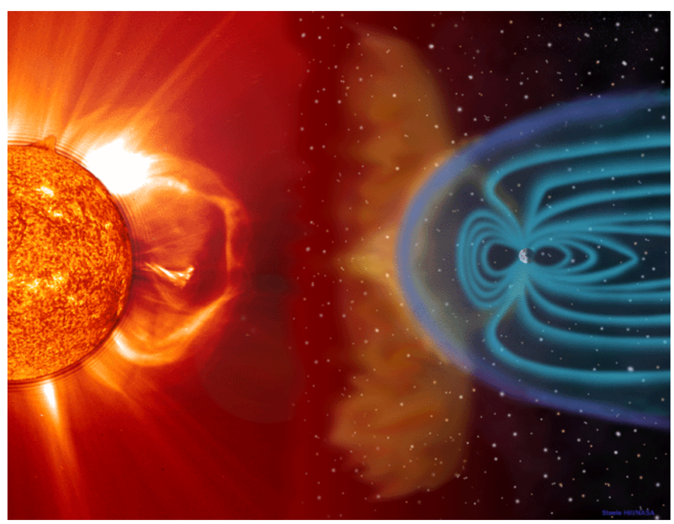

Figure 9: An artistic view of solar flare interaction with Earth atmosphere

8. Conclusions

From the beginning of the discovery [5][6] of solar flare in the solar atmosphere to till now, solar flare is studied very meticulously from the theoretical and observational point of view. Theoretical and observational studies explored solar flare very much. Theoretical study such as study of magnetic reconnection [11][12] and its models [14][15] provided very significant information about the flare which is very much correlated with the observational[10] results. Magneto hydrodynamics models and their numerical salutation [22][23] are very helpful in exploring solar flare phenomenons.

Observational study of flare by observing radiations, fundamental particles, explored solar flare very clearly. Jain, Rajmal et al. [27][28][29] studied X-ray emission from solar flare and explored solar flare from many point of view such as heavy elements presences, thermal and non thermal energy radiations etc. The study of X-ray emissions from solar flare indicates stages in solar flare. High-resolution images obtained from the hard X-ray telescope (HXT) and the soft X-ray telescope (SXT) on Yohkoh and Rhessi revealed several features of solar flare which are consistent with the reconnection model.

Now it is well known that solar flare materialize due to the release of huge magnetic energy and having magnetic reconnection [17] is the prime process behind formation. Solar flare takes place in stages, which are well correlated with observational and theoretical modeling. Solar flare has a loop like structure [17] with thermal variations at different regions in the loop. Electromagnetic radiations take place at different regions in flares. Theoretical modelings of radiations, processes, are very helpful in calculating properties, parameters and extracting information of the flare.

It is also well clear that solar flare causes increased radiation and particle dose in the space. Many phenomenons's such as Aurora, increase in ionosphere concentration level (SID), geomagnetic storms, magnetic reconnection etc. occurs in Earth outer atmosphere.

Still lots of questions are unsolved with respect to Sun and Solar flare. The detail study of Sun is not yet complete. The formation of magnetic field, hydrodynamics of coronal loops, MHD oscillations and coronal seismology, the coronal heating problem, self organized criticality from nano flares to giant flares, magnetic reconnection processes, particle acceleration processes, coronal mass ejections and coronal dimming etc. are the major unsolved problems [33]

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Appendix A

Approximate wavelength, frequency, and energy limits of the various regions of the electromagnetic spectrum.

	Wavelength (m)	Frequency (Hz)	Energy (J)
Radio	$> 1 \times 10^{-1}$	$< 3 \times 10^{9}$	$< 2 \times 10^{-24}$
Microwave	$1 \times 10^{-3} - 1 \times 10^{-1}$	$3 \times 10^{9} - 3 \times 10^{11}$	$2 \times 10^{-24} - 2 \times 10^{-22}$
Infrared	$7 \times 10^{-7} - 1 \times 10^{-3}$	$3 \times 10^{11} - 4 \times 10^{14}$	$2 \times 10^{-22} - 3 \times 10^{-19}$
Optical	$4 \times 10^{-7} - 7 \times 10^{-7}$	$4 \times 10^{14} - 7.5 \times 10^{14}$	$3 \times 10^{-19} - 5 \times 10^{-19}$
UV	$1 \times 10^{-8} - 4 \times 10^{-7}$	$7.5 \times 10^{14} - 3 \times 10^{16}$	$5 \times 10^{-19} - 2 \times 10^{-17}$
X-ray	$1 \times 10^{-11} - 1 \times 10^{-8}$	$3 \times 10^{16} - 3 \times 10^{19}$	$2 \times 10^{-17} - 2 \times 10^{-14}$
Gamma-ray	$< 1 \times 10^{-11}$	$> 3 \times 10^{19}$	$> 2 \times 10^{-14}$

Flare Classification Scheme

Hα classification			**Radio flux at 5000 MHz in s.f.u.**	**Soft X-ray class**	
Importance Class	**Area (Sq. Deg.)**	**Area 10^{-6} solar disk**		**Importance class**	**Peak flux in 1-8 Å w/m^2**

S	2.0	200	5	A	10^{-8} to 10^{-7}
1	2.0–5.1	200–500	30	B	10^{-7} to 10^{-6}
2	5.2–12.4	500–1200	300	C	10^{-6} to 10^{-5}
3	12.5–24.7	1200–2400	3000	M	10^{-5} to 10^{-4}
4	>24.7	>2400	3000	X	$>10^{-4}$

After Bhatnagar & Livingston 2005; Hα sub-classification by brightness: F – faint, N – normal, B – bright
1 s.f.u. = 10^4 jansky = 10^{-2} W m^{-2} Hz^{-}