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Solar Flares

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Abstract

In this paper, the dynamics, the magnetohydrodynamics and the energetics of flaring magnetic loops are reviwed. It is also emphasized that the presented model is in no way a unique one. The most commonly occurring type is labelled as B type flares. This paper reviews the general features of a B type flare.

1. Introduction

A Solar flare is energy releasing impulsive a phenomenon. It has a transitory character. The power that is released in a huge flare amounts to 10^{32} erg in about 10^3 seconds. This value is about 1000 times more than that of the quiet sun. With its preflare, impulsive, flash and main stages it lasts about an hour .

Solar flares develop almost exclusively in magnetically active regions. Preflare observations indicate that the site of energy release is the top(s) of magnetic arcade(s). The free magnetic energy that is stored in the non–potential part of the magnetic loop (for definitions of potential and non potential parts of magnetic loop, see Section III.3) suddenly releases and is converted into heat, to kinetic energy of sub–relativistic particles and to turbulent motions of the plasma as a whole.

The radiative aspect of the phenomenon is very rich. The energy is released from almost every window of the electromagnetic spectrum, i.e. from gamma to radio. That the impulsive phase is simultaneous in microwaves, extreme ultraviolet (EUV) and hard X–rays (HXR). Slow rise of fluxes in euv and soft X–rays (SXR) are the messengers of the onset of a flare.

Solar flare observations concentrate on three fields: 1) Thermal processes in a $T \leq 10^5$ K range; 2) Thermal processes in a $T \geq 10^5$ K range and 3) Non–thermal radiation and particles. On the other hand, theoretical efforts are given to the understanding of such processes as plasma instabilities, magnetohydrodynamics (MHD), magnetic reconnection, particle acceleration and energy release.

Solar flares are not uniform. One differs considerably from another. Observations of solar flares with instruments aboard Solar Maximum Mission (SMM) suggests a possible classification scheme [1][2].

The purpose of the present review is to make the reader acquainted with the various processes taking place during the preflare and the impulsive phases of the phenomenon. In Section II, a brief description of solar flare classification is given. Then in Section III, the dynamics of a magnetic flux tube which is to be the site of a flare is dealt with in an MHD context. In Section IV, the evolution of a flaring loop is treated again in MHD approximation. Section V, is devoted to the radiative processes taking place during the impulsive phase. In the last section, a short summary of the flare scenario is presented.

2. Flare Classification Scheme

The classification is proposed by Tanaka [3] and developed by Tsuneta [4] and Tanaka [5]. This scheme takes into account the whole features, especially the spatial, temporal and spectral properties of HXR.

1.Type A: Hot, Thermal Flares. Temporal: HXR flux that is detected from energy channels less than ~ 40 keV rises and falls slowly. Weak and impulsive HXR components are detected from higher energy channels.

Spectral: The radiation coming from plasma with a temperature less than $T \sim 3-4 \times 10^7$ K and with particles as energetic as 40 keV gives a thermal spectrum; but the spectrum of the radiation coming from particles whose energies are above 40 keV fits with a power law (spectral index, $\gamma \geq 7$).

2. Type B: Impulsive Flares. Temporal: Impulsive spectra display spikey variations in seconds.

Spectral: Slowly increasing flux becomes harder towards the peak and softens again in descending arm. Rising portion of the spectrum of this type is represented by either exponential law or by more than one power laws; descending arm fits with a power law.

Spatial: At the impulsive phase, the radiation comes from the lower chromosphere where the footpoints of the loop are anchored, while

3. Type C: Slowly Varying Hard Flares. Temporal: HXR spectra display variations lasting minutes sometimes half an hour.

Spectral: The spectra over ~ 50 keV hardens in time. In the earlier phase of the flare the spectral index takes values of $\gamma \geq 5$ and then decrease regularly to values of $\gamma \geq 2$.

Spatial: The source is at greater altitudes ($\geq 4 \times 10^4$ km).

Most of the flares display the properties of B Type. In a classificational study on 400 flares, 13 were of C Type; 3 of were A Type; 62 were of associated with microwaves and 338 were of B Type. The greater time and effort of SMM satellite were chanelled to understanding of B Type flares. The above classification scheme, however, is opposed to by De Jager and Svestka [6] on the ground that some flare phenomenon show the characteristics of more than one type. There is no doubt that difficulties arise in this classification. Nevertheless, this scheme does a good job in revealing the inherent features of all three types and at the same time their common features.

3. Dynamics of a Flux Tube

A magnetic flux tube is a prospective site for a solar flare. Its generation, propagation and escape from the convection zone is treated in MHD context.

3.1. Storage in Overshoot Layer

Dynamo theory, without trying to give an account for the source of it, assumes the existence of a global polar field. With a little help from differential rotation, some of this taken–for–granted poloidal field is twisted into toroidal component. This, as we are told is necessary for the maintanence of the magnetic field over an aeon.

Stellar convection zones is believed to be slightly subadiabatic and is considered as a suitable region for magnetic flux storage. Belvedere [7] investigated the effect of the toroidal magnetic fields stored in the overshoot layer just below the convection zones on the eigenfrequencies of stellar oscillations. The frequency splittings of high order acoustic modes that are observed for various main sequence spectral types are attributed to the presence of a non–oblique axisymmetric toroidal magnetic field.

3.2. Magnetic Buoyancy

The dynamics of the above mentioned toroidal flux tube may be treated in the magnetohydrostatic context. Equation of motion under the gravitational force, plasma pressure and Lorentz force is given by (Priest, [8]):

$$\rho \frac{d\nu}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g} \tag{1}$$

Here, ρ is mass density, ν is plasma velocity, p is pressure, $\mathbf{j}$ is current density, $\mathbf{B}$ is magnetic induction and g is gravitational acceleration. Since the existence of magnetic loops is a well known fact, we may assume that gravitational force is weak, compared to the other forces, so that the flux rope can manage to rise to the surface of the sun. To see this let us investigate the dynamics of the rope in a steady state and in the absence of gravitational force. In this case equation (1) may be rewritten as below :

$$\nabla(p + \frac{B^2}{2\mu}) = \frac{1}{\mu}(\mathbf{B} \cdot \nabla)\mathbf{B} \tag{2}$$

In a flux rope the right hand side of equation (II.2) vanishes, i.e., $\mathbf{B}$ does not vary along $\mathbf{B}$. Equation (2) then says that,

$$p + \frac{B^2}{2\mu} = const. \tag{3}$$

Now imagine that the flux tube is beneath the photosphere at some height in convection zone. Let the pressure and magnetic field within the tube be denoted by p_i and B_i and the pressure outside be p_0. In that case total lateral pressure balance can be written as $p_0 = p_i + (B_i/2\mu)$. If the relevant layer is isothermal and the mass densities in and out of the flux tube are denoted by ρ_1 and ρ_0 respectively, the above equation is written as,

$$\frac{k_B T \rho_0}{m} = \frac{k_B T \rho_i}{m} + \frac{B_i^2}{2\mu} \tag{4}$$

It is obvious from equation (4) that the mass density is higher than inside the flux tube. Consequently, the unit volume of plasma within the magnetic flux tube feels a net buoyancy force of $(\rho_o - \rho_i)\mathbf{g}$. Bearing in mind the fact that equation (3) holds true and the flux rope is rising through the convection zone wherein the density falls towards the photosphere, it is easily seen that the magnetic flux rope becomes tighter and tighter.

3.3. Kink Instability

Magnetic flux rope is rising towards the photosphere because all the way through the convection zone the mass density within the tube is less than that of outside. This tube is susceptible to kink instability which may be likened to a hydrodynamic instability called Rayleigh-Taylor instability. In the above mentioned configuration-space instability a lighter fluid is given the task of supporting a heavier one. In our case, the magnetic tube assumes the role of the lighter fluid.

If kink instability develops at some point of the rope and if field aligned currents are also present within the rope the very same currents produce a poloidal field. Newly produced poloidal field is stronger at the bottom of the rope than the top. The magnetic pressure thus produced increases the size of the kink and the plasma within the tube is pushed towards the top of the loop. This brings about the diffusion of plasma from the top of the tube and thus further lightness of that part. Lighter flux tube becomes more susceptible to magnetic buoyancy force. The balance between the plasma pressure and the magnetic pressure changes in favour of the later and closed field lines at the top of the rope "opens".

It is believed that flare energy is stored as magnetic energy in the stressed magnetic fields of active regions. One reason for this belief is that there seems to be no other competing energy sources that would power flares. The second reason is that an order of magnitude estimates of the magnetic energy content of typical active regions suggest that it is comparable to or exceeds the observed energy of most flares [9]. Besides, it is only the "free" magnetic energy that is stored in the non potential part of the field that powers the flare. Non potential part of the field is the one where large coronal electric currents flow. The potential part of the loop contains no electric currents and it is in lowest energy state.

4. Evolution of the Loop

4.1. Current Sheet Formation

The open magnetic field lines lie on a plane called "current sheet". These lines form X-type singular lines. If, due to temporal changes of the magnetic field, a vortex electric field is produced then "infinite" conductivity of plasma implies that huge electric currents will flow in the sheet. In that case, magnetic field lines will assume the role of short circuits. Extremely intense and irregular currents run through these circuits [10]. Magnetic field changes in the current sheet may be described by the induction equation:

$$\frac{d\mathbf{B}}{dt} = \nabla \times (\nu \times \mathbf{B}) + \eta \nabla^2 B \tag{5}$$

This equation shows that the magnetic field changes due to advection and diffusion. In the current sheet magnetic field diffuses away and its energy is converted into heat ohmically. There are a myriad of models trying to account for the magnetic field reconnection in the current sheet. An interested reader may refer to reference 8 for the list of models. The ones that seem to be more consistent with observations build up a simple diffusion region of length 2L and width 2l between oppositely directed fields.

First of all, suppose the input flow speed and magnetic field are ν_i and B_i respectively. Equation of motion gives us the outflow speed as ν_{Ai} which is Alfven speed at the inflow. Conservation of mass implies that the rate $(4\rho L\nu_i)$ of mass inflow must be equal to the rate $(4\rho l\nu_0)$ at which mass outflows.

$$L\nu_i = l\nu_{Ai} \tag{6}$$

Let us examine the energetics of reconnection process in a Sweet-Parker diffusion layer $l \ll L$ [11]. Equation (6) implies that $\nu_i \ll \nu_{Ai}$ so that the inflow speed is much smaller than the Alfven speed. The rate of inflow of electromagnetic energy is given by Poynting flux, i.e., $E \times H$; or, since $E = \nu_i B_i$ in magnitude,

$$E\frac{B_i}{\mu}L = \nu_i \frac{B_i^2}{\mu}L \tag{7}$$

Therefore, the ratio of inflow of kinetic to electromagnetic energy is,

$$\frac{\frac{1}{2}\rho\nu_i^2}{B_i^2/\mu} = \frac{\nu_i^2}{2\nu_{Ai}^2} \ll 1 \tag{8}$$

In other words, most of the inflowing energy is magnetic. Next, let us consider the energy outflow. Conservation of magnetic flux implies that,

$$\nu_0 B_0 = \nu_i B_i \tag{9}$$

This, in return, implies that $B_0 \ll B_i$. Also the outflow of electromagnetic energy is much less than inflowing one. So, what has happened to the inflowing energy? The ratio of outflowing kinetic to inflowing magnetic energy is,

$$\frac{\frac{1}{2}\rho\nu_0^2(\nu_0 l)}{\nu_i B_i^2 L/\mu} = \frac{\frac{1}{2}\nu_0^2}{\nu_{Ai}^2} = \frac{1}{2} \tag{10}$$

Equation (10) shows that half of the inflowing magnetic energy is converted to kinetic energy and the other half to thermal energy. Also shown by equation (10) is the fact that magnetic reconnection creates hot and fast plasma particles. From Ampere's law and Faraday's law we can derive the Poynting vector flux which is given below :

$$-\nabla\cdot(E\times H) = E\cdot j + \frac{d}{dt}(\frac{B^2}{2\mu}) \tag{11}$$

which implies that an inflow of electromagnetic energy can produce electrical energy $E\cdot j$ for the plasma and a rise in the magnetic energy. On the other hand, $E\cdot j$ can be decomposed into components as below:

$$E\cdot j = \frac{j^2}{\sigma} + \nu\cdot(j\times B) \tag{12}$$

so that the electrical energy appears partly as ohmic heat and partly as the work done by the Lorentz force. If we remember that the messengers of a flare are the rising fluxes of SXR and EUV. It is this ohmic dissipation that heats up the plasma and precedes the rapid reconnection.

5. Impulsive Phase

Following the magnetic reconnection in the current sheet, the free energy that is stored in the non-potential part of the field is released. This sudden release of energy generates nonthermal and sub-relativistic particles at the top of the loop. Depending on the pitch angle they acquire they will either fall into the loss cone or seek their respective mirror points.

Let us first concentrate on those particles which fall into the loss cone (Loss cone is the cone, the vertex angle of which is defined as, $B_0/B_m = sin^2\theta$; where B_0 and B_m are the field intensities at the top and at the footpoints of the magnetic loop. θ is the angle between the particle instantaneous velocity vector and magnetic field vector B_0. These particles cannot be trapped by the loop's magnetic field. Once accelerated at the loop top, they speed down the field lines towards the higher density regions of lower corona or upper chromosphere. We should mention in passing that solar flares are almost exceptionally coronal or chromospheric phenomena.

a) Non thermal electrons. Since the corona is a low density plasma where collisional relaxation is slow and the confining magnetic field is so strong as to inhibit the dissipation processes we expect that the nonthermal distribution of particles is highly likely to occur and to be long-lived enough to be detected. Indeed, Ca XIX (3.18 Å) and Fe XXV (1.85 Å) lines taken during solar flares by Bent Cyrstal Spectrometer aboard SMM and also Ca XIX, Ca XX (3.02 Å), Fe XXV and Mg XII (8.42 Å) lines taken by Bragg Cyrstal

Spectrometer aboard P78-1 spacecraft have shown line broadenings. The broadenings are attributed to the turbulent motions generated by fast nonthermal particles. In addition, the same lines show nonthermal broadenings on the blue wings. Calculations indicate that observed blue wing broadenings are caused by upflowing hot plasma with a speed of $400kms^{-1}$ and a temperature of 10^7 K. It is very interesting to observe that the same lines show neither general broadenings nor non thermal broadenings on the blue wing for limb flares. This is indicative that the turbulent motions are predominantly on radial direction [12].

On the other hand, X-Ray Imaging Spectrometer (HXIS) on the SMM has resolved separate sources of 16-30 keV X-ray emissions identified with the footpoints of magnetic loops where energy carrying electrons enter the chromosphere [13].

b) $H\alpha$ Observations. We may group $H\alpha$ observations into two groups: i) $H\alpha$ absorption lines and ii) $H\alpha$ images. Now, first $H\alpha$ absorption lines. In the disk observations these lines are absorption lines. But, during the impulsive phase of the flare these lines quickly grow into emission lines. The red wing of an $H\alpha$ absorption line displays Doppler broadening. If taken into account together with the Ca XIX lines, $H\alpha$ absorption lines reveal very valuable information about the plasma motions in opposite directions. $H\alpha$ absorption lines and Ca XIX SXR lines are excellent tools to test the consistency of Chromospheric Evaporatiom Model (CME). In the next subsection we'll see that the additional support given to CME comes from the observations of Type III radio bursts.

$H\alpha$ spectra were taken with Fairchild 202 CCD at the reimaged focal plane of the echelle spectrograph at NSO/SP. The data consist of $H\alpha$ spectra with 97.6 mÅ resolution over a 10 Å range and spectroheliograms with 50×50 square pixels with 2".55 resolution [14]. All four flares observed in this programme showed $H\alpha$ red asymmetry. From the number of pixels showing asymmetry calculated were the chromospheric areas where the energy deposited and the volume of flaring magnetic loops. Typical values are, $1.1 \times 10^7 cm^2$ and $6.3 \times 10^{25} cm^3$ respectively. The average value of the maximum Doppler shift velocity is $42kms^{-1}$ and the characteristic decay time is 36 ± 16 s.

$H\alpha$ images of the impulsive phase of a solar flare show bright patches. In most of the cases these patches are in the form of "double ribbon". On the basis of coaligned magnetograms, SPO $H\alpha$ spectroheliograms and HXIS X-ray images loop structures with two well defined footpoints are identified. Since their angular separation is known their linear dimension is immediately estimated. Again the typical values are 10" and 5.7×10^8 cm respectively. It is very enlightening to see that in the isointensity map of hard X-ray the two compact sources are cospatial with the double ribbons imaged by Mitaka $H\alpha$ pictures [1]. This coincidence shows that the same electron population forms both hard X-ray patches and double ribbons.

c)Decimetric Radio Emission. In the impulsive phase of a solar flare, the plasma in a magnetic loop is in a turbulent motion with velocities exceeding 100 km s^{-1}. The same plasma also shows high-speed upflows with bulk velocities of 300-400 km s^{-1} as inferred from the line broadenings and blueshifts of soft X-ray lines in Ca XIX and Fe XXV .

Until very recently, the chromospheric evaporation process has been studied chiefly in SXRs and $H\alpha$. Aschwanden and Benz [15] have provided for the first time observational evidence for CME at radio wavelengths. Decimetric type III bursts are believed to be produced by plasma waves. Plasma waves in turn are produced by electron beams. The scenario goes as follows: when the free energy stored at the non potential part of the loop is released, particles are accelerated to sub relativistic speeds by various accelerating agents. Accelerated electrons spiral down the magnetic field lines towards the footpoints of the loop in shapes of beams. Then the beam excites plasma waves at local plasma frequencies. These plasma waves are converted into escaping electromagnetic waves at radio frequencies. The basic characteristic of this phenomenon is the frequency drift. Upgoing beam excites plasma waves progressively with lower frequencies. Finally, it reaches a minimum frequency value. After that frequency drift starts again towards higher frequency values. Dynamic spectra of the decimetric bursts looks like an inverted U. As a matter fact, depending on the character of the magnetic field line and the life time of the beam, spectra may look like a letter J or inverted U or a letter N. Whatever the shape of the spectra, one thing is quite clear that decimetric type III bursts are unambiguous tracers of electron beams. Take, for instance, a N burst. Beam starts at the footpoint of a loop, travels up to the corona to the loop top then comes down to the mirror point at the other foot, is reflected back, travels up again to the loop top and by then it loses its beam characteristic so that it cannot excite plasma waves that is to be converted to electromagnetic waves any more.

Slowly drifting high frequency cut off at decimetric wavelengths is interpreted in terms of an opacity effect resulting from the upflowing hot flare plasma during the chromospheric evaporation processes.

From the drift rate one can determine the electron density, the speed of the beam and the speed of the upflowing plasma. The values inferred from the radio data are consistent with Ca XIX SXR measurements.

6. Summary

A solar flare is impulsively energy releasing a phenomenon. Its energy is derived from the non potential part of the flaring loop. The released energy goes to heating the chromospheric-coronal plasma, to kinetic energy of particles and to turbulent motion of the plasma as a whole. Two types of particles put their signatures to the following radiative processes during and after the impulsive phase. Those which fall into the loss cone produce HXR compact regions and $H\alpha$ "double ribbons" at each sides of the inversion line; and those which are trapped produces a myriad of radio bursts. Former particles cause the chromospheric plasma evaporate and produce SXR covering much larger area than HXR compact regions. A flare lasts about an hour during which a thousand times more energy that that of quiet sun is released.

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