A Review on Mechanisms of Turbulence Generation in Solar Corona

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Abstract:- The unusual heating of solar corona is always a fascinating question in front of astrophysics community. In fact, this high temperature (T > 10^6 K) of solar corona is directly associated with the generation of solar wind.

There are models like Landau damping of plasma waves, anisotropic turbulence and many more available to explain both the phenomena, the unexpected heating of the corona and solar wind acceleration. Existence of waves in and around this region is believed to be reasonable cause for this extraordinary heating. Turbulence generation as a result of nonlinear interaction between these waves found to be most significant phenomena for this abnormal heating. The present article accommodates some paramount conclusions that shows the impression of turbulence to assist the heating of particles in solar coronal regime.

***Keywords:-** Plasma Waves, Turbulence, Solar Corona.*

I. WAVES IN CORONA

The presence of different modes of waves have always involved to get the possible solution for the many unsolved mysteries around space. The possible cause for waves to become an important reason for coronal heating is that magnetohydrodynamic (MHD) waves are the mediator of energy transfer from convective zone beneath the Sun's photosphere up to the solar atmosphere at the time of travelling into the magnetized plasmas. There, the Alfvén waves could turn into shock waves that dissipate their energy as heat that will cause to increase the temperature of the corona. Different waves that deliver heat to the coronal particles sounds impressive but there should be some results for the sake of accuracy with this wave based model.

SOHO (solar and heliospheric observatory) and TRACE (Transition Region and Coronal Explorer) missions have been predicted the presence of different type of oscillations which is having small amplitude in the coronal loop region. Slow MHD waves have been experimentally observed by the data of these spacecrafts and the resolution of these spacecrafts are very high in both space and time domain. The low-frequency modes of magnetized plasmas, Alfvén waves, were theorized by Alfvén, 1947 [1] and dissipates in corona. Due to their dissipation, Alfvén wave considers effective candidate in the puzzle of coronal heating. Observations confirm the presence of Alfvén waves in the solar corona [2]. Observations of Hinode spacecraft have also predicted the role of Alfvén waves in the heating of coronal plasma [3]. MHD waves and ion acoustic waves are generated in the photosphere and the waves which are produced in the photosphere must be dissipated in the outer atmosphere to increase its temperature. Therefore, ion acoustic waves have also been considered of great interest to heat the solar coronal region [4]. Rial *et al.*, 2010 [5], examined the temporal evolution of coupled three-dimensional propagating fast and Alfvén waves in a potential coronal arcade. They concluded that due to the involvement of three-dimensional dependency on the perturbed quantities, as a result, coupling of fast and Alfvén waves takes place and the obtained solutions demonstrate a mixed fast/Alfvén characteristics. The investigated medium is non-uniform and coupling of resonant nature produces so that energy transfer and damping of wave exhibit in the considered medium.

II. HEATING BY MAGNETOHYDRODYNAMIC TURBULENCE

Solar coronal heating problem can be analyzed by giving the attention only on two major points that is what is the source of that energy which is available for anomalous heating of corona and from where it comes i.e., the reason behind the mechanism to produce sufficient energy which will assist the heating of the particles. In this article, the discussion is around possible mechanisms only as compared to the source. Turbulence is always fascinating factor to affect the coronal heating. It plays an important role to create cascading of energy to heat the particles in and around corona.

Coronal heating is believed to be affected by magnetohydrodynamic turbulence [6]. Interaction of kinetic Alfvén wave with electrons has been considered an important acceleration mechanism and participated in the coronal heating problem affectively [7]. Footpoint motions are accepted as a most possible cause in the photosphere to provide energy into the large scale modes. Now the magnetohydrodynamic turbulence transfers this energy to the modes of small scales. Active regions, quiet-sun regions and coronal holes are three different classification of solar corona. Active regions are just the ensembles of loop like structures in the photosphere which connects the points of opposite magnetic polarity. Hollweg, 1984 [8] predicted that Kolmogorov turbulent dissipate rate is good enough to meet the heating requirements for coronal active region loops. The Kolmogorov flux is found to be lying in the range of requirement to heat the active region. He calculated in the following manner:

The dissipation rate in turbulent cascade depends only on how rapidly the energy is cascaded.

$$E\left(k_\perp\right)=c_0\varepsilon^{2/3}k_\perp^{-5/3}$$
(1)

Where $E\left(k_\perp\right)$ represents the energy per unit mass and ε shows the energy dissipation rate per unit mass.

$$\left\langle\delta v^2\right\rangle=\int_0^\infty\left(E\left(k_\perp\right)dk_\perp\right) \qquad \longrightarrow$$

$$\varepsilon=k_{\perp 0}\left(\frac{2\left\langle\delta v^2\right\rangle}{3c_0}\right)^{3/2}$$
(2)

$\left\langle\delta v^2\right\rangle$ is the non-thermal velocities in coronal loops and $k_{\perp 0}$ is wave number at which energy injection starts. It is something like $2\pi/diameter$ of the active region loops. The typical values are-

$$\left\langle\delta v^2\right\rangle\approx1.8\times10^{13}\,cm^2\,s^{-2},$$

$$k_{\perp 0}\approx2.1\times10^{-9}\,cm^{-1}.$$

Volumetric heating rate comes out to be-

$$\rho_0\varepsilon\approx 8\times10^{-4}\,ergs\,cm^{-3}\,s^{-1}$$ where loop density $$\rho_0=5\times10^{-15}\,gm\,cm^{-3}.$$

If the heating extends over the entire loop length then energy flux density is $U\approx8\times10^{6}\,ergs\,cm^{-2}\,s^{-1}\approx 8000\,W/m^2$.

Thus on the behalf of above analysis, Hollweg [8] predicted that the Kolmogorov turbulent dissipation rate is enough for the heating of particles in the coronal active region but the mechanisms for the generation of this turbulence in coronal region were the unsolved mysteries for the scientists around the world. To investigate the possible mechanisms for Kolmogorov turbulence in solar corona, many researchers considered waves as a key factor and studied the interaction between them.

III. GENERATION OF KOLMOGOROV TURBULENCE BY WAVE'S INTERACTION

The interplay of inertial Alfvèn wave with slow magnetosonic wave has been studied by Sharma *et al.*, 2016a [9] in solar corona. These waves were propagating in all the three directions. This interaction gives rise to the filamentation like instability. The analysis of field intensity of inertial Alfvén wave shows the localized structures with the pre-existing slow magnetosonic waves in the background. The pattern of energy transferring to the small scale modes is also predicted with this model. An attempt has been made to calculate the thermal tail of charged particles in solar coronal space with the help of second scaling in the spectrum of magnetic power which was found after the first break point. Thus due to the nonlinear coupling between these two waves, filamentation and formation of thermal tail takes place. In this model, the interaction between coronal particles and the localized fields studied with fractional diffusion approach. How the power law tail generated because of turbulence related to the fractional diffusion mechanism has been understood by Bian and Browning, 2008 [10].

In this diffusion mechanism, at the given time, the relation between the distribution function $\left[g(v,t)\right]$ with the spectral index $\left[\mu\right]$ is given by $g(v)\sim v^{-(1+\mu)}$. The power spectrum studied by Sharma *et al.*, 2016a [9] shows that spectral index is having the numerical value $\left[\mu=3\right]$ (see Fig. 1), therefore the resultant distribution function can be represented as $g(v)\sim v^{-4}$. Hence there would be the enhancement of the thermal tail of the charged particles, which might be play an important role to accelerate the particles.

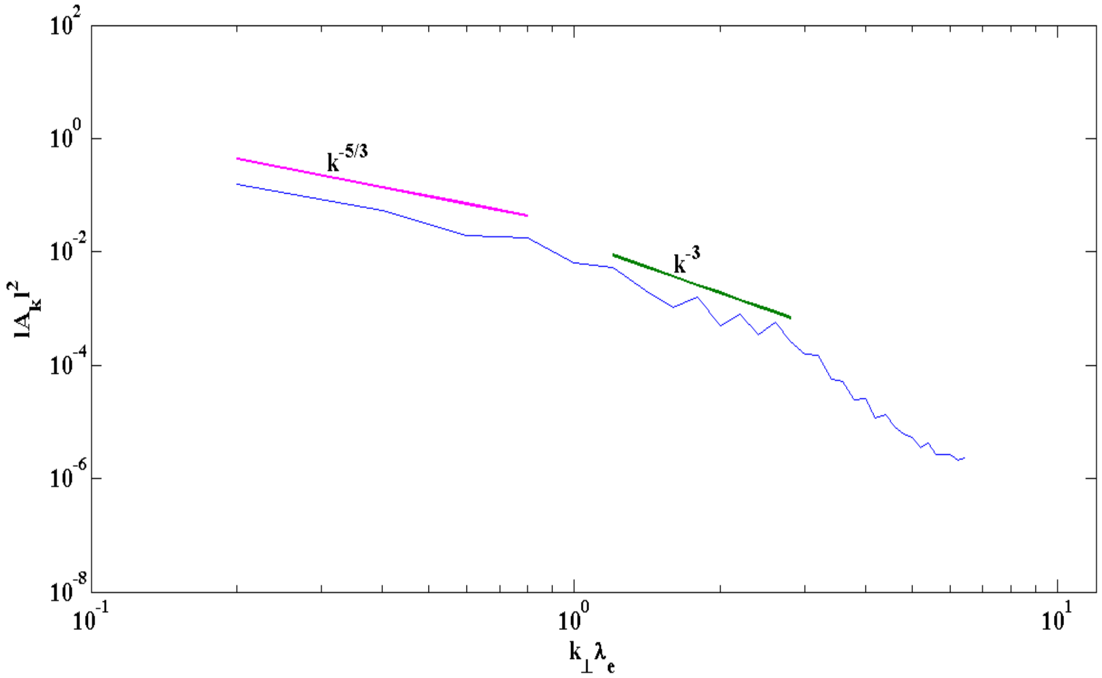

Fig 1:- The plot of $\left|A_k\right|^2$ and the perpendicular wave numbers taking the average over all parallel wave numbers [9].

Fokker–Planck diffusive mechanism is one of the mechanisms which can explain the particle acceleration. Sharma and Kumar, 2010 [11] has made an attempt to study the Fokker–Planck diffusive formalism in auroral plasmas. They described the interaction in a continual manner between auroral particles and localized structures of intense fields using the diffusion theory with a quasi-linear approach, represented as $\frac{\partial f}{\partial t}=\frac{\partial}{\partial v}\left(D\left(v\right)\frac{\partial f}{\partial v}\right)$; here D(v) represent the diffusion coefficient and f (t,v) is the distribution function in velocity space. Since the characteristic time is neglected in comparison to observation time and hence distribution function becomes independent of time and represented as f (v) ∝ $v^{2-\eta}$.

Numerous predictions have been put forward by the researchers to investigate the mechanisms of particle acceleration. Fisk and Gloeckler, 2008 [12] have been found the compressional turbulence causes the particle acceleration in a thermally isolated environment with the spectral shape f (v) ∝ $v^{-5}$of the thermal tail. Acceleration with a high speed of the charged particles has also been discussed as a result of evolution of power spectrum with the advancement of time.

Sharma et al., 2016b [13] discussed the coupling of three dimensionally propagating kinetic Alfvén wave and ion acoustic wave which is also propagating in all three dimensions in solar coronal loops. Field structures of kinetic Alfvén wave gets localized in the influence of its changed phase velocity as a result of variations in background density. From the obtained results from numerical simulation, the size of the localized structures on transverse scale is found to be of the order of gyro radii scales. Laser beam filamentation is quite analogous to this localization process in the presence of nonlinearity, where there is a race between the nonlinear effects and diffraction. When the beam's transverse size is higher than critical value, the nonlinear effects command the diffraction effects and as a result, localization of the beam takes place. Energy spectrum has also been tried to study with one restriction i.e., by taking the average over all parallel wavenumbers (when the spectrum shows quasi steady state of turbulence) as an outcome of coupling of these two waves with the presence of ponderomotive nonlinear force. Energy cascade has been obtained with the scale of $k^{-5/3}$(known as Kolmogorov scaling) up to $k_\perp \rho_s < 1$ as shown in fig. 2.

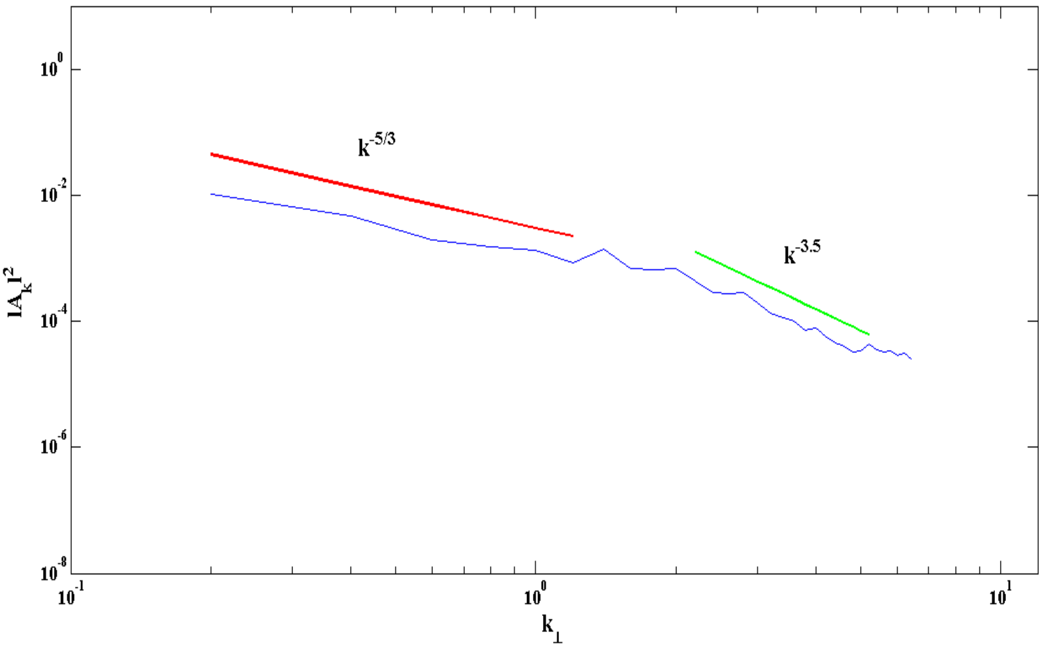

Fig 2:- The plot of $\left|A_k\right|^2$ and the perpendicular wave numbers taking the average over all parallel wave numbers [*13*].

The interaction between the high frequency (~0.01 Hz) and low frequency (~0.001 Hz) slow magnetosonic waves have been examined in the solar coronal loops by Sharma *et al.*, 2017 [14]. They adopted two-fluid model to study this self modulation of slow magnetosonic waves, simulate the normalized equations of both the waves with numerical technique of pseudo-spectral method. This attempt was made to predict the reason behind the Kolmogorov turbulence via self modulation of experimentally observed slow magnetosonic waves in the region of coronal loop. These waves interact with each other via ponderomotive nonlinear force which is arises due to high frequency of pump wave. The low frequency wave is travelling in the ambient magnetic field and its dynamics changes due to this ponderomotive force. This interplay between high and low frequencies waves gives rise to the focusing type results of high frequency wave and field localized structures appeared. Variation analysis of energy verses wavenumber has also been checked. The reason behind to study this spectrum is exactly to know the idea about scaling around the inertial range. As expected, the scale of energy cascading is just the Kolmogorov type (-5/3) in the inertial range of the power spectrum (see Fig. 3). The compatibility of Kolmogorov dissipation rate with heating requirements has already been discussed above, hence this wave based model is quite reliable for generating the turbulence in coronal loops.

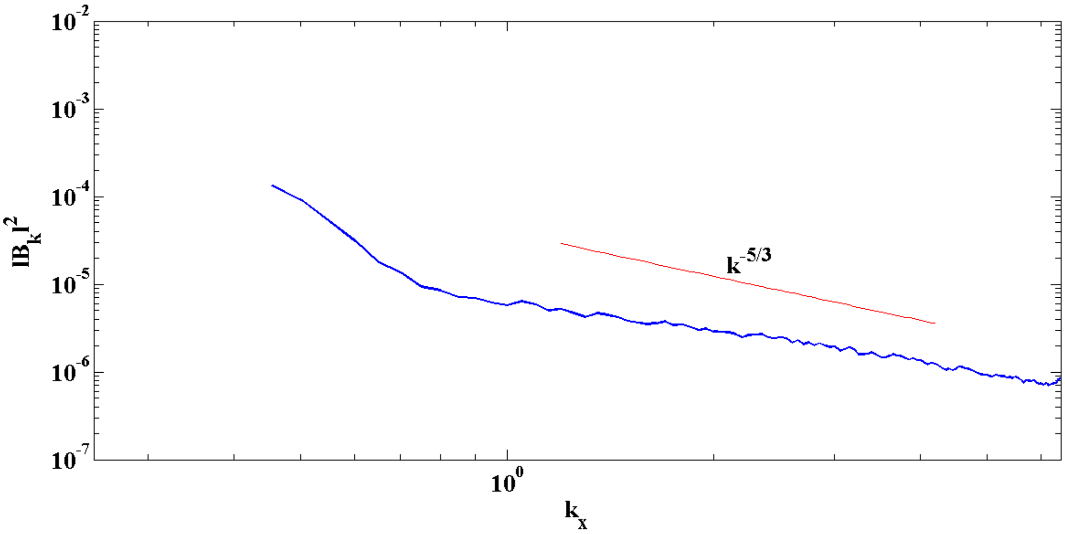

Fig 3:- The plot of $\left|B_k\right|^2$ versus k_x with average of all k_z [*14*].

IV. FINAL REMARKS

How MHD turbulence is helpful in the process of coronal heating, it is clearly explained by Hollweg, 1984 [8]. The main objective of this article to discuss the various mechanisms to generate turbulence in the region of solar corona. Waves that are observed in and around corona can interact with each other via some nonlinearity and give rise to energy cascading at the same scale which is compatible with the required dissipation rate for heating. NASA’s Parker Solar Probe is the first ever breakthrough mission to touch the sun. Cranmer, 2018 [15] showed some theoretical predictions about MHD turbulence in the regions to be explored by *PSP*. He studied 3-D power spectra with perpendicular wavenumber of incompressible Alfvén waves and fast-mode waves as a function of radial distance from the sun and confirmed the importance of kinetic Alfvén wave in energy cascading. Therefore waves interaction can be consider most effective way for generating turbulence in coronal plasma that will gradually increase the transportation of energy and ultimately heat the particles.

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