MAGNETOHYDRODYNAMIC WAVES AS ENERGY SOURCES IN SPACE PLASMA

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Abstract - Transferring energy in space plasma via radiation mechanisms is not efficient, instead traveling magneto-hydrodynamic (MHD) waves have shown good efficiency in transferring energy between regions where the classical radiative transfer laws are not fulfilled. Magnetic field lines frozen in plasma are subject to squeezing, puffing, and twisting by turbulence. This interaction is found to generate different wave modes, for example longitudinal, transverse and torsional waves. In the current work we present ab initio numerical computations of the generation of MHD waves, and evaluating the amounts of wave energy fluxes and spectra. The aim of the current work is to shed light on the different mechanisms of generating wave energies in space plasmas. The obtained results are vital for space-related laboratory research, space explorations, solar and stellar studies and for future in laboratory high energy generations and storage based on supersonic shock waves in plasma.

Index Terms - Magneto hydrodynamic waves, space plasma wave energy generation.

I. INTRODUCTION

Besides solid, gas and liquid, ionized matter called plasma exist under extreme physical conditions of high temperatures and presumes in space and in labs. Plasmas are nonlinear media and with the existence of magnetic fields they are able to sustain different wave modes. Space is full of turbulent fluid that interact with magnetic field lines and generate waves. High energy shock waves generation in a laboratory will open the door to new sources of energy. Numerous laboratory experiments have been performed trying to simulate the space processes on earth trying to realize terrestrial sources of high energy shock waves.

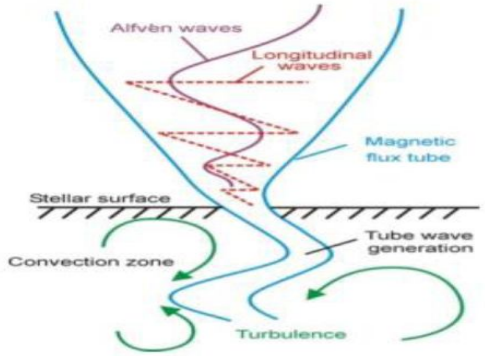


Figure 1. The interaction between turbulence and the magnetic field lines as a source of wave generation.

When comparing laboratory and space studies. In the current work we present theoretical studies of space plasma and show how interaction between magnetic field structures are interacting with turbulence to generate waves with different modes. Advances in laboratory studies will be also discussed, the validation of theoretical models with laboratory results is a very important step in understanding the real mechanisms of wave generation and propagation (Koepke 2008).

II. METHODOLOGY OF WAVE GENERATION

Our approaches are based on basic thermodynamics parameters, namely, the effective temperature of the plasma T_{eff}, the gravity log g, and the magnetic field strength B_0 of the structure.

A. Modeling turbulence

In the current study, we follow Musielak et al.~(1994), and assume a convective region where the spatial turbulent energy spectrum is of the Kolmogorov type and that the main energy carrying bubbles should have a (vertical) size of the local scale height. In reality, there must be some modification of the Kolmogorov law to allow for bubbles larger than this characteristic scale. Since larger bubbles rise from deeper layers where the scale height is larger, it is increasingly more difficult for them to penetrate to the surface. This means that for bubbles with sizes larger than the scale height, the turbulent energy spectrum should decrease. Based on these physical arguments, they proposed that E(k) should be given by:

$$E(k) = \begin{cases} 0 & 0 < k < ak_t \\ b\frac{u_t^2}{k_t}\left(\frac{k}{k_t}\right) & ak_t \le k < k_t \\ b\frac{u_t^2}{k_t}\left(\frac{k}{k_t}\right)^{-5/3} & k_t \le k \le k_d \end{cases}, \qquad (1)$$

and that $a = 0.2$ and $b = 0.758$ for the so-called extended Kolmogorov turbulent energy spectrum. We take the extended Kolmogorov spectrum (see Eq. 1) with a linear rise from $k/k_t = a = 0.2$ to 1, where $k_t = 2\pi/H_{surf}$ and $H_{surf} = \Re T_{eff}/(\mu g)$, with $\Re$ being the gas constant and a molecular weight $\mu = 1.3$. Based on this assumption, the largest bubbles have the vertical size $H_{surf}/a = 5H_{surf}$.

The modified Gaussian frequency factor is given by

$$G\left(\frac{\omega}{ku_k}\right) = \frac{4}{\sqrt{\pi}}\frac{\omega^2}{|ku_k|^3}e^{-\left(\frac{\omega}{ku_k}\right)^2}, \quad (2)$$

where u_k is computed from

$$u_k = \left[\int_k^{2k} E(k')dk'\right]^{1/2}. \quad (3)$$

According to Musielak et al. (1994), this form of the frequency factor G is chosen because it has a maximum contribution at $\omega = ku_k$. From a physical point of view, this means that one gets maximum correlation when a bubble of gas with size $\lambda = 2\pi/k$, moving with velocity u_k, has just traveled by a distance equal to its own diameter at a time $t = 2\pi/\omega = \lambda/u_k = 2\pi/(ku_k)$. The Gaussian shape is assumed to account for the fact that most (but not all) bubbles have similar lifetimes

B. Basic magnetohydrodynamic equations

In this section we focus on the key equations describing the longitudinal MHD tube waves propagating along the vertically directed magnetic flux tubes. The equations to be solved in the Euler frame for continuous 1D flows are given as:

$$\frac{\partial \rho A}{\partial t} + \frac{\partial \rho u A}{\partial x} = 0, \quad (4)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + g(x) = 0, \quad (5)$$

$$\frac{\partial S}{\partial t} + u\frac{\partial S}{\partial x} = \left.\frac{dS}{dt}\right|_{\text{rad}}, \quad (6)$$

$$\Phi = A \cdot B = \text{const}, \quad (7)$$

$$\frac{B^2}{8\pi} + p = p_e = \epsilon p. \quad (8)$$

Note that p and p_e are the gas pressures inside and outside the tube, respectively, B is the magnetic field strength, and $\epsilon = p_e : p$ denotes the pressure ratio between outside and inside of the tube. Furthermore, the cross section A is time-dependent owing to the distensibility of the tube.

Moreover, Eqs.7 and 8 represent the conservation of the magnetic flux φ and the horizontal pressure balance between inside and outside the tube. All quantities are both functions of height x and time t. This system of equations is solved using the method of characteristics.

III. RESULTS AND CONCLUSIONS

Our results show that magnetohydrodynamic waves with different modes can carry huge amounts of energies among different regions in space and work as connecting channels from regions with low radiative temperatures to regions with higher temperatures where the classical radiative transfer laws are not fulfilled. The energies of the magnetohydrodynamic waves in form of longitudinal and transverse modes are larger than the acoustic energies by factors ranges from 1.6 to 1.8. The efficiency of wave generation increases with the existence of magnetic fields. In the current study we assume three different values of the magnetic field strength, namely,

η	F_{ac}	F_{LTW}	F_{TRAN}
0.75	$8.3 \cdot 10^8$	$7.0 \cdot 10^8$	$1.3 \cdot 10^9$
0.85	$8.3 \cdot 10^8$	$3.4 \cdot 10^8$	$1.5 \cdot 10^9$
0.95	$8.3 \cdot 10^8$	$1.1 \cdot 10^8$	$1.4 \cdot 10^9$

Table 1 A comparison between the wave energy fluxes (in erg cm^{-2} s^{-1}) for acoustic (F_{ac}), for longitudinal (F_{LTW}) and transverse (F_{TRAN}).

B_0 = 0.75, 0.85, 0.95 B_{eq} with

$$B_{eq}(z = 0) = \sqrt{P_e/8\pi}$$

being the equipartition field strength for a plasma free magnetic structure. Increasing the magnetic field pressure inside flux tubes enhances the stiffness of the tubes, which makes it difficult for the external turbulence squeezing the magnetic field lines.

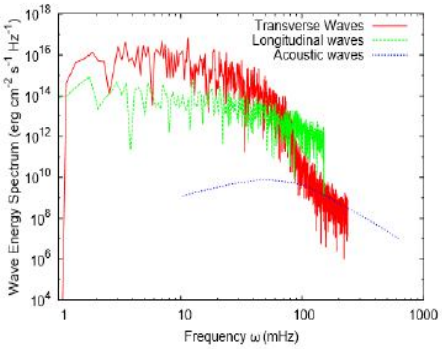


Fig. 3 A comparison of the generated longitudinal, transverse and acoustic wave energy spectra for a plasma with effective temperature T_{eff} = 6543K and magnetic field strength B = 1281 G.

Appendix A

In this section we present the algorithms used for the current study. The computations start by characterizing stars with their basic parameters, namely the effective temperature T_{eff}, surface gravity log g, metal abundance $m. For the construction of convection zone models we employ the classical mixing-length theory and the mixing-length parameter α needs to be accurately determined. Algorithm 2 describes the steps we follow for computing convection zone model C, turbulence T, and their interactions to compute the longitudinal tube wave energy fluxes and spectra.

The construction of the initial magnetic models is described by

Algorithm 1: `Main`

input : $\mathcal{T}_{eff}$: Effective temperature; $\mathcal{G}$: Surface gravity; $\mathcal{Z}_m$: Metallicity; $\mathcal{B}$: Magnetic field strength; α: Mixing length parameter

output: $\mathcal{UPW}$: Upward propagating wave spectra; $\mathcal{E}$: Time-averaged energy flux.

begin
  $\langle \mathcal{M}, \mathcal{U}_t, \mathcal{V}_{\|} \rangle \leftarrow InitialModels(\mathcal{T}_{eff}, \mathcal{G}, \mathcal{Z}_m, \mathcal{B}, \alpha)$;
  $\langle \mathcal{UPW}, \mathcal{E} \rangle \leftarrow ComputeInteractions(\mathcal{M}, \mathcal{U}_t, \mathcal{V}_{\|})$;
  return $\langle \mathcal{UPW}, \mathcal{E} \rangle$
end

Algorithm 2: `Initial Models`

input : $\mathcal{T}_{eff}$: Effective temperature; $\mathcal{G}$: Surface gravity; $\mathcal{Z}_m$: Metallicity; $\mathcal{B}$: Magnetic field strength; α: Mixing length parameter

output: $\mathcal{M}$: Magnetic flux tube; $\mathcal{U}_t$: Convection zone; $\mathcal{V}_{\|}$: Turbulence.

begin
  $\mathcal{M} \leftarrow generate_mft(\mathcal{T}_{eff}, \mathcal{G}, \mathcal{Z}_m, \mathcal{B})$;
  $\mathcal{U}_t \leftarrow generate_convection(\mathcal{T}_{eff}, \mathcal{G}, \mathcal{Z}_m, \alpha)$;
  $\mathcal{V}_{\|} \leftarrow generate_turbulence(\mathcal{U}_t)$;
  return $\langle \mathcal{M}, \mathcal{U}_t, \mathcal{V}_{\|} \rangle$
end

Algorithm 3: `ComputeInteractions`

input : $\mathcal{M}$: Magnetic flux tube; $\mathcal{V}_{\|}$: Turbulence; β: integer.

output: $\mathcal{UPW}$: Upward propagating wave spectra; $\mathcal{E}$: time-averaged energy flux.

begin
  $t \leftarrow t_{initial}$;
  $\mathcal{W} \leftarrow empty$;
  $\mathcal{E} \leftarrow empty$;
  while $t \leq \beta$ **do**
    $\mathcal{W}^t \leftarrow mhd(t, \mathcal{M}, \mathcal{V}_{\|})$;
    $\mathcal{E}^t \leftarrow avg_energy_flux(\mathcal{W}^t)$;
    increment t;
  $\mathcal{W}' \leftarrow interpolate(\mathcal{W})$;
  $\mathcal{W}'' \leftarrow apodize(\mathcal{W}')$;
  $\mathcal{P} \leftarrow fft(\mathcal{W}'')$;
  $\mathcal{PW} \leftarrow high_pass_filter(\mathcal{P})$;
  $\mathcal{UPW} \leftarrow fft^{-1}(\mathcal{PW})$;
  return $\langle \mathcal{UPW}, \mathcal{E} \rangle$
end

Fig. 2 The algorithms used for the computations of the wave generation, Credit: Fawzy 2013

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