6^{th} Asia-Pacific Conference on Plasma Physics, 9-14 Oct, 2022, Remote e-conference

Mode Conversion of MHD Waves and Shocks in the Solar Atmosphere

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As a crude idealization, the atmosphere of the Sun consists broadly of the photosphere, from which most visible light originates, a roughly isothermal chromosphere of some 15 density scale heights width, a narrow transition region (TR) where the temperature rises steeply, and an extended diffuse corona reaching a million degrees or more (Figure 1). Powerful magnetic field structures, commonly associated with active regions (sunspots) and convective cells (granulation and supergranulation), complicate the picture, but for the most part we deal with a plane-stratified picture here.

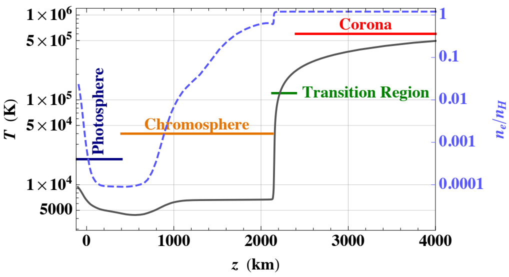

Figure 1 Semi-empirical mean model of the solar atmosphere temperature T structure [1] with height z, depicting the various layers. The dashed blue curve represents the electron to neutral hydrogen ratio n_e/n_H (right axis), which is as low as 10^{-4} in the low chromosphere.

Two classes of model aim to explain how a cool photosphere can heat a hot corona to such extreme temperatures, and both involve magnetism: Direct Current (DC) models where large numbers of reconnection events yield local heating, and Alternating Current (AC) models, where acoustic and magnetic waves carry mechanical energy upward from the near-surface convection to the corona. Both models are probably operating. We focus on AC.

Most wave power is found at frequencies measured in milliHertz (mHz), corresponding to periods of minutes. In this regime, single-fluid magnetohydrodynamics (MHD) is an adequate description in many respects, since collisional frequencies are much higher.

There are three types of MHD waves: slow, Alfvén (or intermediate) and fast, referring to their phase speeds. In a uniform plasma, these are independent modes. However, the strong stratification of the chromosphere in particular provides opportunities for linear interactions between each pair, i.e., *mode conversion*.

For an isothermal gravitationally stratified atmosphere with uniform inclined magnetic field, Figure 2 illustrates this in z-k_z space, where k_z is the vertical wavenumber. The various loci are the solutions of the dispersion relation $\mathcal{D}(a(z), c(z); \omega, k_x, k_y, k_z)=0$ with given frequency ω and horizontal wavenumbers k_x and k_y Alfvén speed profile $a(z)$ and sound speed $c(z)$, thereby specifying relations between k_z and z.

For example, there is a close avoided crossing between slow and fast waves near $a=c$ (z=0) on the upward branch in the depicted case, which allows strong fast/slow mode conversion. It is much weaker on the downward branch as the gap is wider. Similarly, the upgoing fast and Alfvén loci are near coincident around z/H=1, and so fast/Alfvén conversion may occur if there is an available coupling mechanism. In ideal MHD, fast/Alfvén coupling requires sin $\phi \neq 0$ [2], but in Hall MHD it occurs for any ϕ [3].

In this contribution, we will survey the various mode conversion types, both ideal and Hall, and also discuss how this carries over to shock waves [4]. Conclusions will be drawn for the heating of the solar atmosphere.

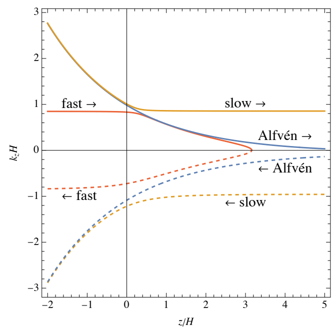

Figure 2 Dispersion diagram for isothermal atmosphere with uniform inclined magnetic field B_0 (sin θ cos ϕ , sin θ sin ϕ , cos θ) with θ = 20° and ϕ = 45°, sound speed c, density scale height H (typically about 120 km in the photosphere and low chromosphere). The Alfven speed a increases exponentially with height, and Alfvén/acoustic equipartition $a = c$ is located at z = 0.

References

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[3] P. Cally and E. Khomenko, *ApJ*, vol. 814, p. 106, 2015.

[4] J. Pennicott and P. Cally, *ApJL*, vol. 881, p. L21, 2019.