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The effect of plasma expansion on the dispersion properties of MHD waves

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The Sun and other stars release a continuous stream of charged particles, known as solar or stellar wind. This plasma expands at high velocities through interplanetary space, and exhibits turbulence, instabilities, and oscillations, such as Alfvén or magnetosonic waves. Although extensively studied, it continues to present fundamental challenges in plasma physics, particularly on the dynamics of its expansion and the role of phenomena such as turbulence and electromagnetic waves in this process.

In this context, the Expanding Box Model (EBM) offers an innovative theoretical framework for studying plasma expansion in a non-inertial frame of reference that co-moves with the plasma, but at a fixed volume[1]. This approach has proven to be especially useful in numerical simulations, as it avoids memory constraints[2].

In this work, we employ the set of ideal expanding magnetohydrodynamic equations, derived from first principles by Echeverría-Veas et al.[3] within the EBM framework, to theoretically characterize the effects of radial solar wind expansion on its characteristic linear waves.

Through the analytical derivation of dispersion relations, we explore the changes in wave propagation across a range of heliocentric distances on the normal magnetohydrodynamic modes: the Alfvén mode and the fast and slow magnetosonic modes, as obtained from the ideal MHD equations. Our findings reveal a spatial dependence in the derived dispersion relations that aligns with both the literature and the traditional non-expanding case, thereby helping to bridge the gap between theory and observation in solar wind dynamics (see Figure 1). Notably, our analysis uncovers a pronounced acceleration of the fast magnetosonic wave starting at approximately 15 AU, highlighting the significant influence of expansion on solar wind dynamics.

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References

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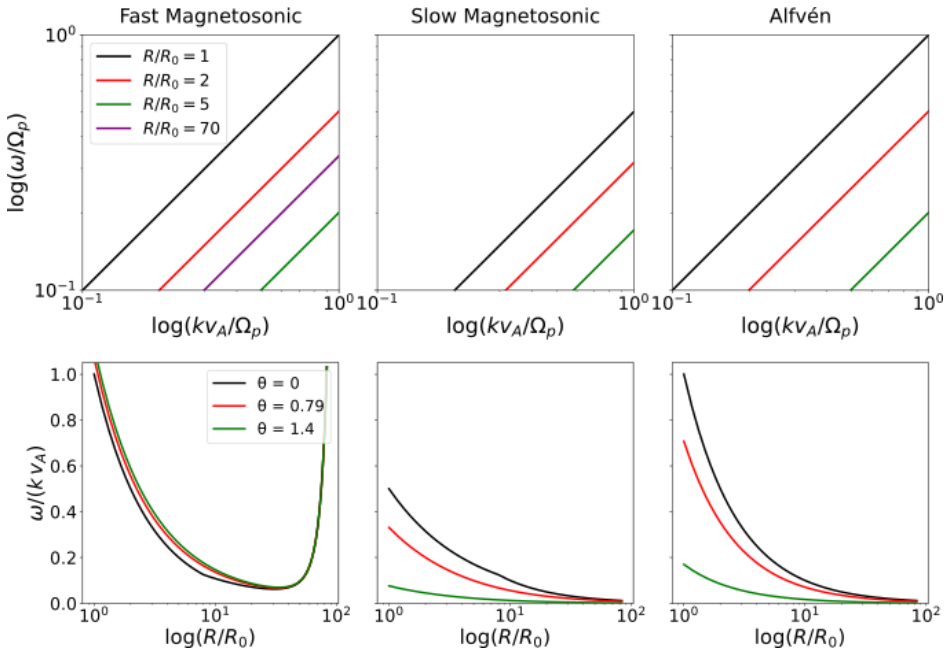

Figure 1: Normalized dispersion relations (log-log scale) for each mode with θ fixed at 0°, i.e. the angle between the background magnetic field $\mathbf{B}_0$ and the wave vector $\mathbf{k}$ (top), and the corresponding normalized phase velocities for various θ values (bottom), as functions of heliocentric distance (R_0 = 0.3 AU) . Note that the fast magnetosonic wave accelerates around 15 AU.