On the propagation of slow extraordinary mode in inhomogeneous plasma and implications for the wave magnetic field measurements onboard PSP

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Abstract: Langmuir or slow extraordinary modes (sometimes called z-modes) are continuously observed in the solar wind. These coherent waves are expected to have a weak magnetic component, which had never been observed so far. For the first time we reveal their magnetic signature by using the SCM search-coil magnetometer onboard Parker Solar Probe. Using simulations of wave propagation in inhomogeneous plasma, we show that this magnetic component of the slow extraordinary mode is primarily due to density inhomogeneities that occasionally cause the refractive index to drop to low values. This drop, as we are going to show, facilitate the observations of the magnetic signatures which are usually hidden in the noise floor.

Introduction

The dominant electrostatic mode (big refractive index) at around the plasma frequency ω_p is the Slow extraordinary mode (SE). This waves are continuously observed on PSP thanks to the burst registered by the Time domain sampler (TDS). Figure 2 is an example of these observations.

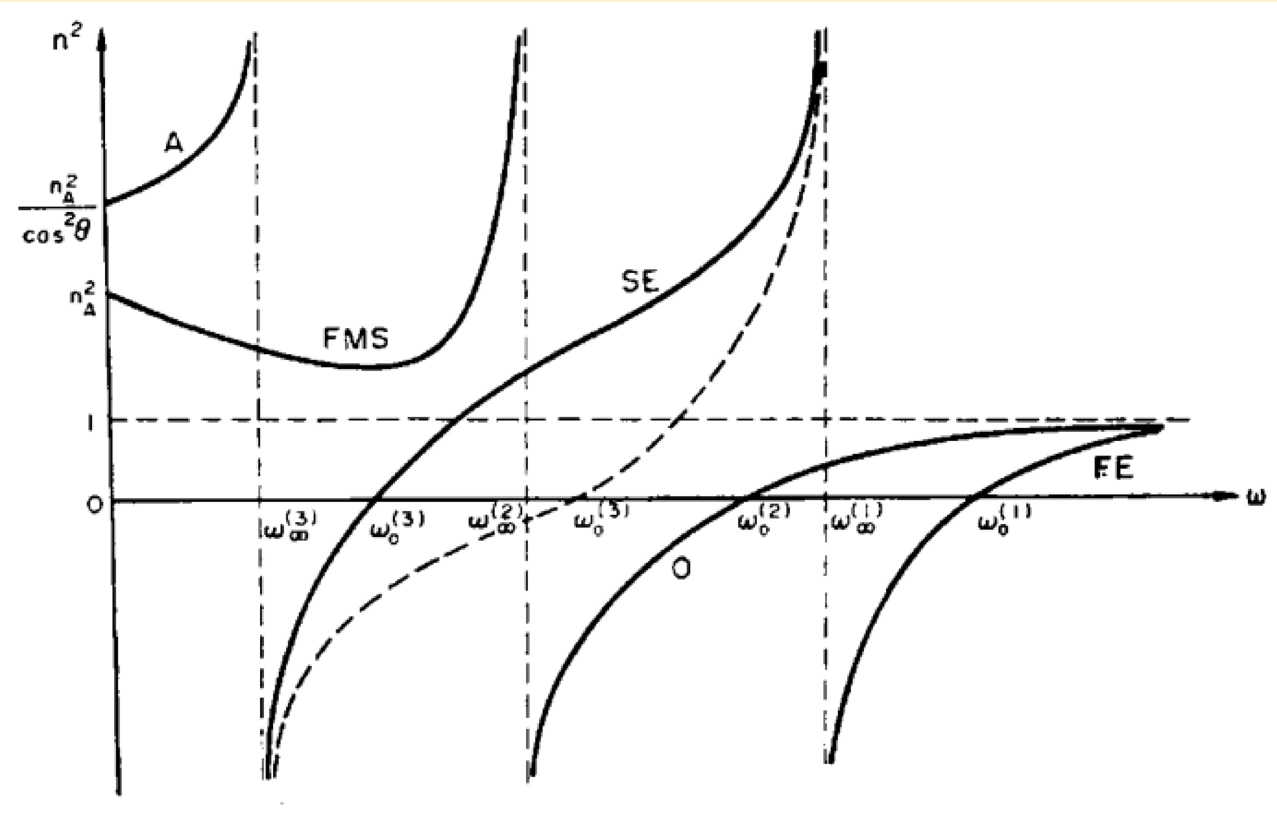

Fig 1: Dependence of the refractive index on the frequency for a cold magneto-active plasma. The SE, of interest here, goes to resonance at the plasma frequency ($\omega^{(1)}_\infty \approx \omega_p$).

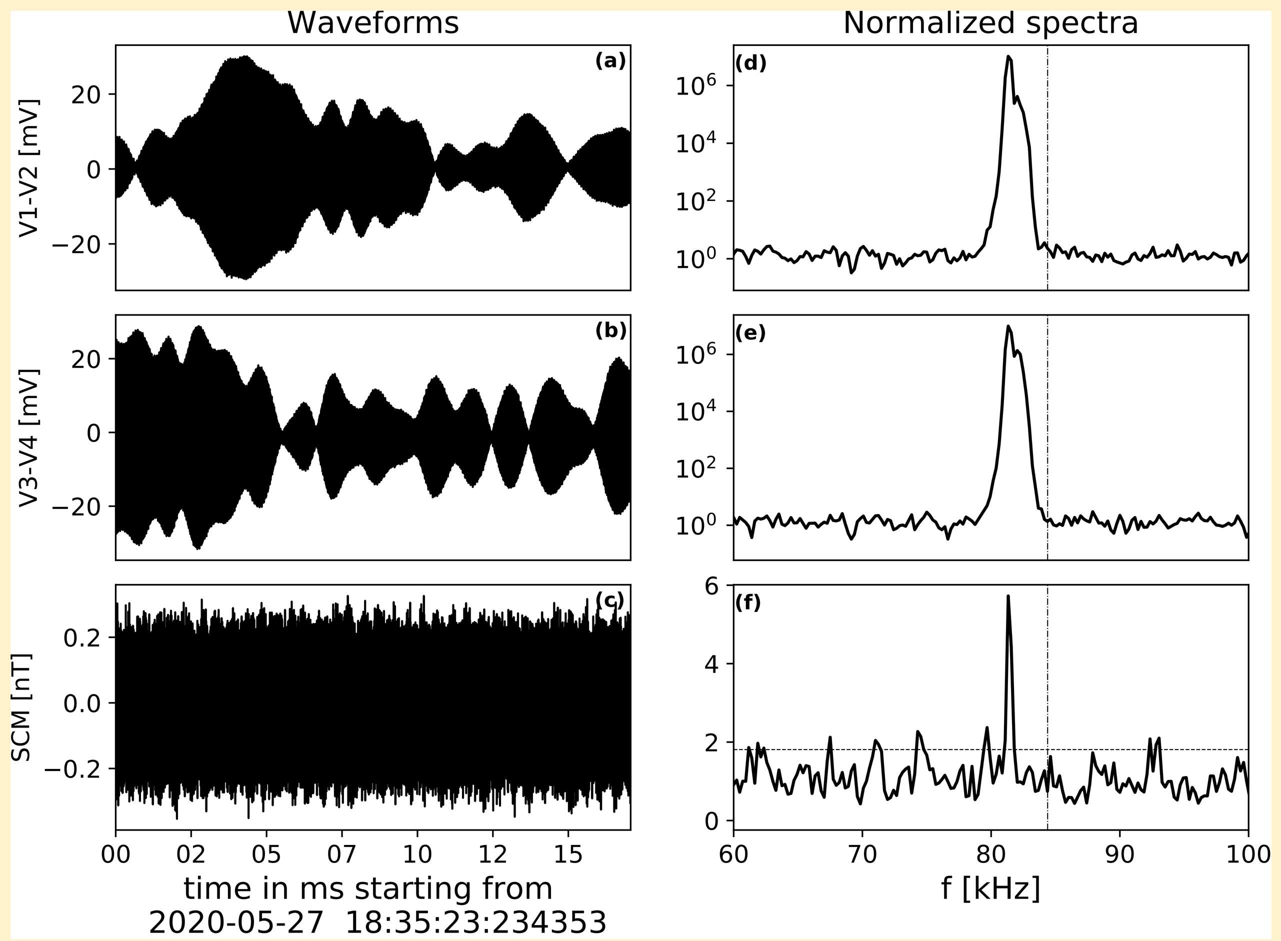

Fig 2: TDS data (left column), respective normalized power spectral density (right column). In panel (a) the potential difference between Antennas 1 and 2 in mV, same for Antennas 3-4 on panel (b) and magnetic fluctuations measured from the high frequency coil of SCM on Panel (c) in nT. In panel (d), (e) and (f) the respective spectra are normalized by the 30th percentile of all the events of the day (this normalization "kill" the interferences related to the spacecraft). The vertical dotted line correspond to the plasma frequency. The presence of magnetic signature is evident.

Observations

We looked for magnetic signatures in all the TDS bursts available since the beginning of the mission up to May 2021, and out of thousands of events only for 26 bursts we found a magnetic signatures clearly above the noise.
These bursts were found in two days 27 (18 events) and 28 May 2020 (8 events). In both days type III radio burst are measured before the appearance of the SE bursts (see figure 3 for may 27). Most likely the same beam that generated the radio burst close to the sun subsequently generated the slow extraordinary mode in situ.

In many previous works (e.g. Bale et al. 1998) the existence of a magnetic signature was inferred from the elliptical or circular polarization of the electric field, but a direct measurement (like the one in figure 1) is unprecedented.

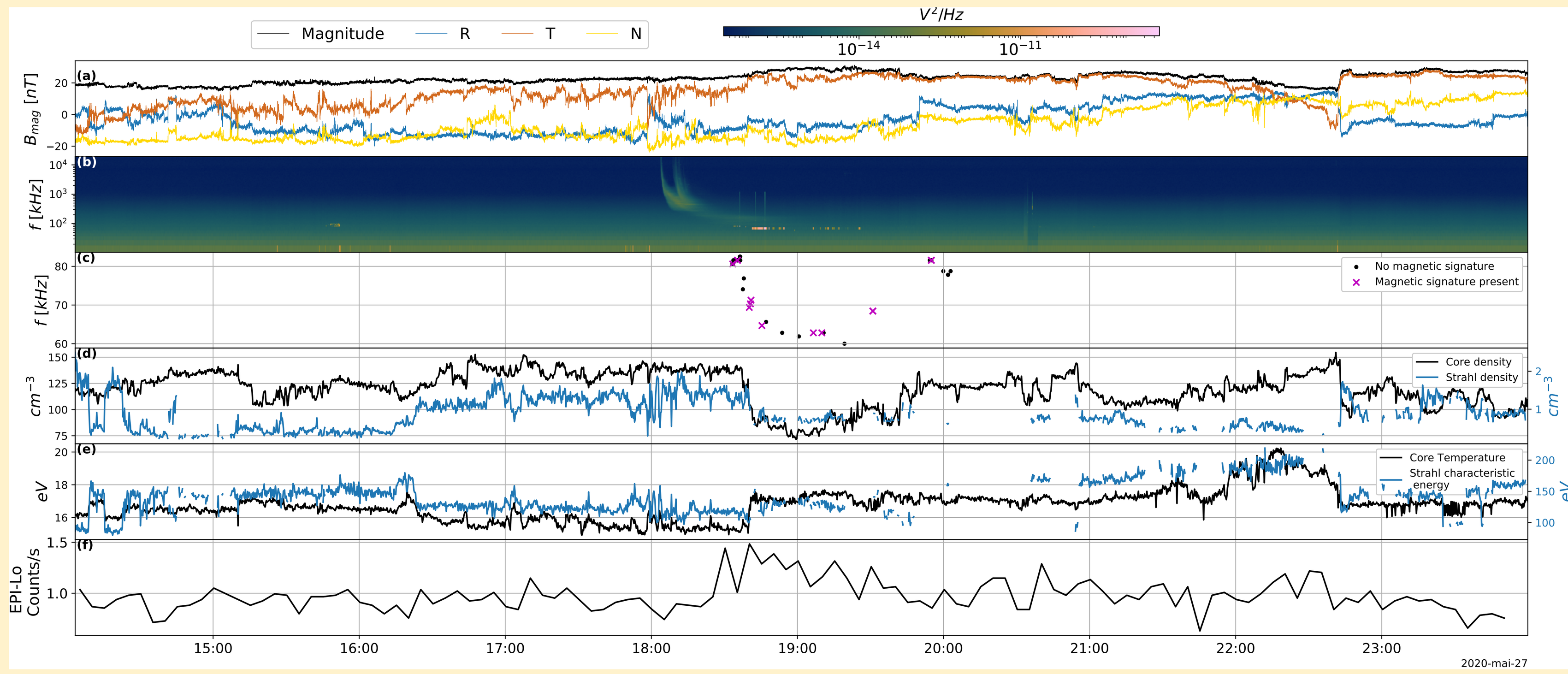

Fig 3: From top to bottom: magnetic field in RTN coordinates, Radio Frequency Spectrometer data, Peak frequency of the observed burst in TDS, strahl and core electron density, core temperature and strahl characteristic energy, EPI-Lo counts integrated on all look directions and energy. Figure 3 reveals that the plasma on which the SE are observed is highly inhomogeneous (density drop and magnetic field enhancement) and the presence of energetic particles.

Theoretical approach and simulation

The key to understand the appearance of the magnetic signature is in the relation between the magnetic and electric fluctuations and the refractive index. Combining the dispersion relation equation (Equation 1), the Faraday law and the Linearized Vlasov-Maxwell system in the Fourier space for a cold plasma we obtain relation 1. This relation tells us that in order to have more chances to observe a magnetic signature we need a strong electric fluctuation coupled with a drop in the refractive index (N = ck/ω). This drop can be obtained in presence of inhomogeneities.

$$\delta B \propto \frac{\delta E}{N} \qquad \text{Relation 1}$$

To study the variation in the refractive index we start from the dispersion relation.
The dispersion relation for nearly electrostatic waves in plasma at high frequency, neglecting the contribution of the ions, with a magnetic field along the z-axis, is expressed in Equation 1.

$$\omega = \omega_p\{1 + \frac{3}{2}k_\parallel^2\lambda_D^2 + \frac{\Omega_e^2}{2\omega_p^2}\frac{k_\perp^2}{k^2}(1 - \frac{\omega_p^2}{k^2c^2})\} \qquad \text{Equation 1}$$

Treating ω as an Hamiltonian, we can study the propagation of the wave in presence of inhomogeneities by solving the relative Hamilton equations (eq 2 and 3).

$$\frac{d\vec{x}}{dt} = \frac{\partial \omega}{\partial \vec{k}} \qquad \text{Equation 2}$$

$$\frac{d\vec{k}}{dt} = \frac{-\partial \omega}{\partial \vec{x}} \qquad \text{Equation 3}$$

We solve these equations numerically in a bi-dimensional space (x, z) where x is the direction orthogonal to the magnetic field and z the parallel direction. In this space we chose a profile for the density variations and the variations of the magnetic field. Figure 4 we show an example of the result.

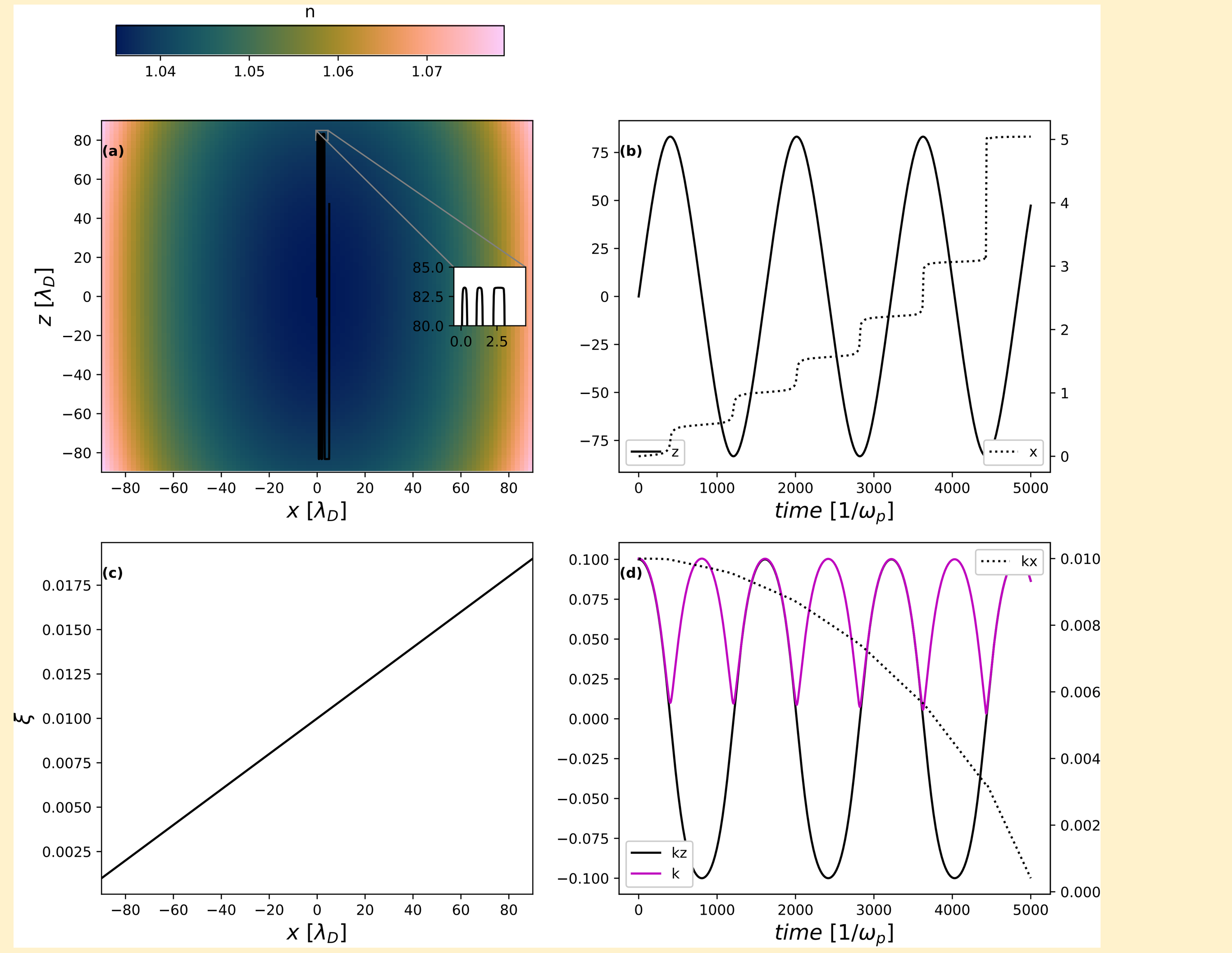

Fig 4: Panel (a) and (c) normalized density and B variations (fixed), the black line in panel (a) is the trajectory of the wave reflected back and forth. Paned (b) and (d) evolution in space of kx and kz. Panel (e) wave position in space. Panel (f) evolution of kx, kz and k².

From figure 4 panel (f) we can see that when the wave is reflected at the density gradients k², and therefore the refractive index, become smaller increasing the chances of observing a magnetic signature.

Conclusions

We reported the observations of magnetic signatures for the slow extraordinary/langumir mode and we proposed a theoretical frame to understand their occurrence. We suggest with the aid of calculations and simple simulation that the key ingredient to observe this magnetic signatures is a drop of the refractive index due to inhomogeneities in thye plasma density. The next step is to compare in a more quantitative fashion the result of the simulation with the data of the few events available.

Acknowledgment
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