



Magnetohydrodynamic Wave Modelling in the Solar Atmosphere and their Observational Consequences

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St Andrews



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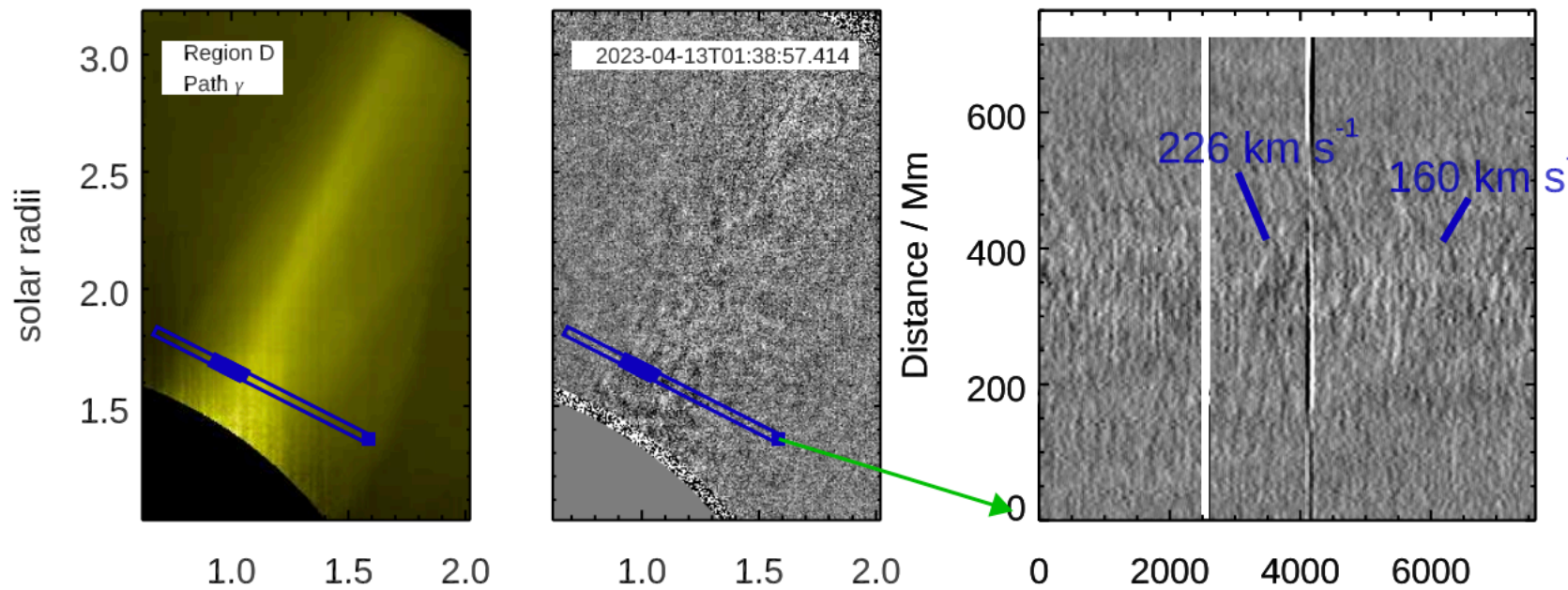
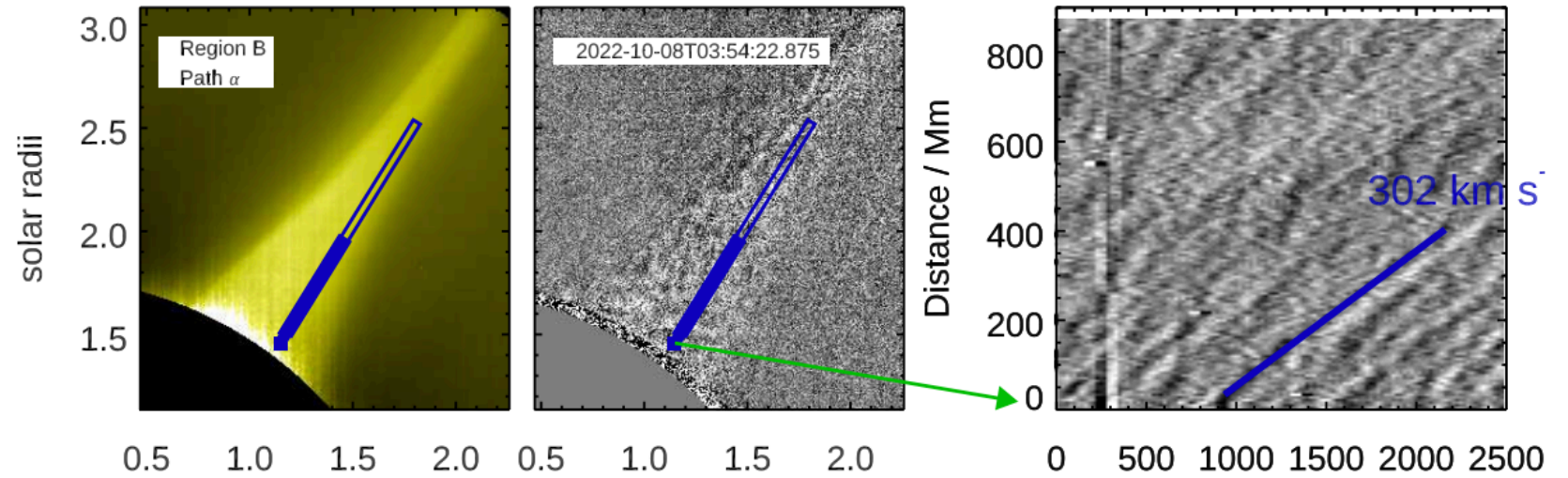
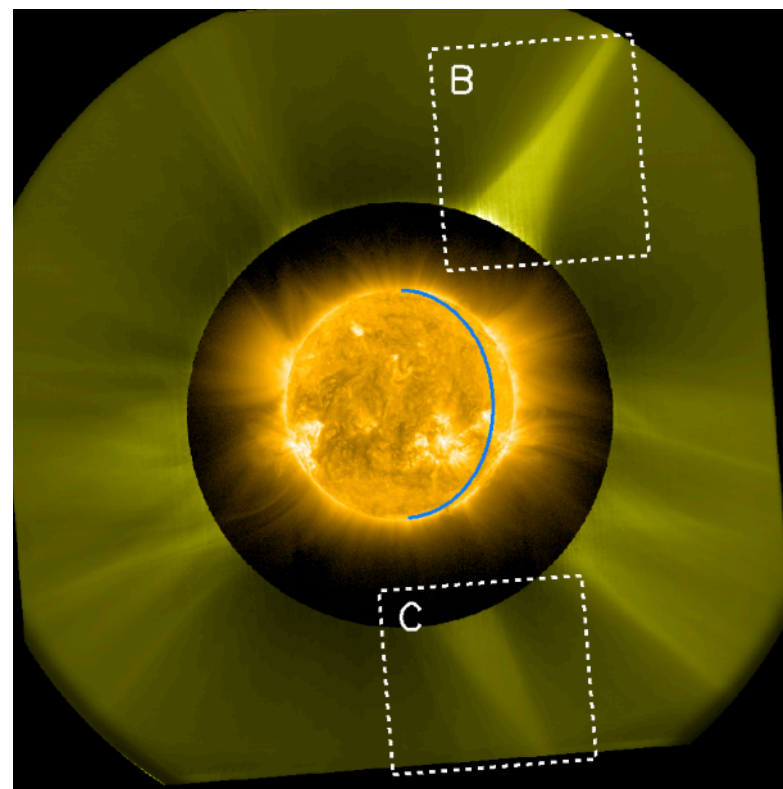
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DI RIPRESA E RESILIENZA



Università
degli Studi
di Palermo

Thomas Howson,
Paolo Pagano,
Ineke De Moortel,
Simon Daley-Yates

Waves in a Helmet Streamer (Metis Andretta et al., 2025)



1. What can MHD modelling tell about these waves?
2. What role do these waves play in global coronal dynamics – heating, solar wind acceleration?

Getting a Helmet Streamer

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

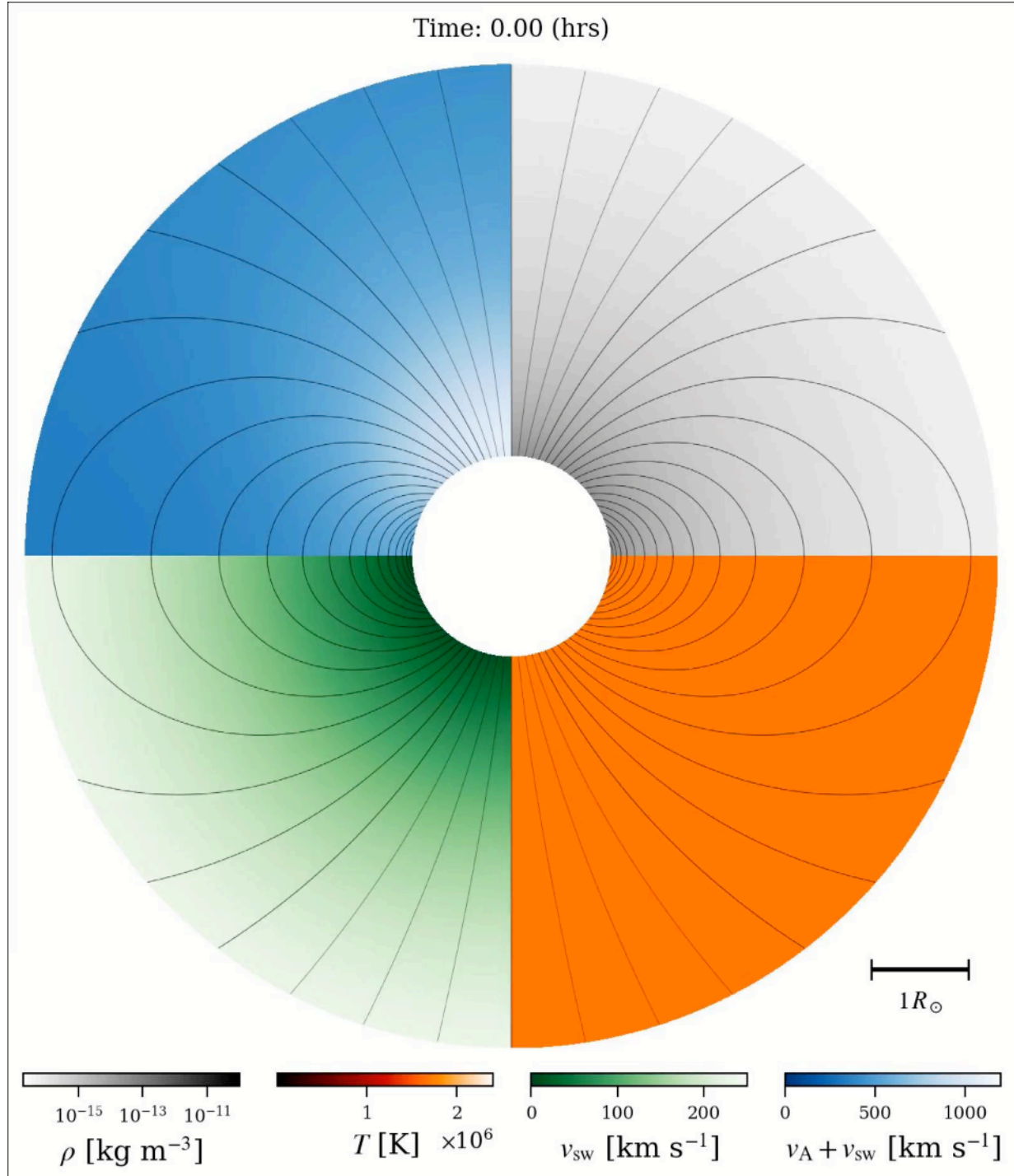
$$\frac{\rho^\gamma}{\gamma - 1} \frac{d}{dt} \left(\frac{p}{\rho^\gamma} \right) = -\nabla \cdot \mathbf{q} - n^2 \Lambda(T) + \eta j^2 + H_{\text{bg}}$$

$$\frac{d}{dt} (\rho \mathbf{v}) = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g} + \rho \mathbf{S}_w(r, \theta, t)$$

$$H_{\text{bg}} = \frac{f_0}{H_0} \left(\frac{R_\odot}{r} \right)^2 \exp \left(-\frac{r - R_\odot}{H_0} \right)$$

PLUTO Code

(Mignone et al. University of Turin)



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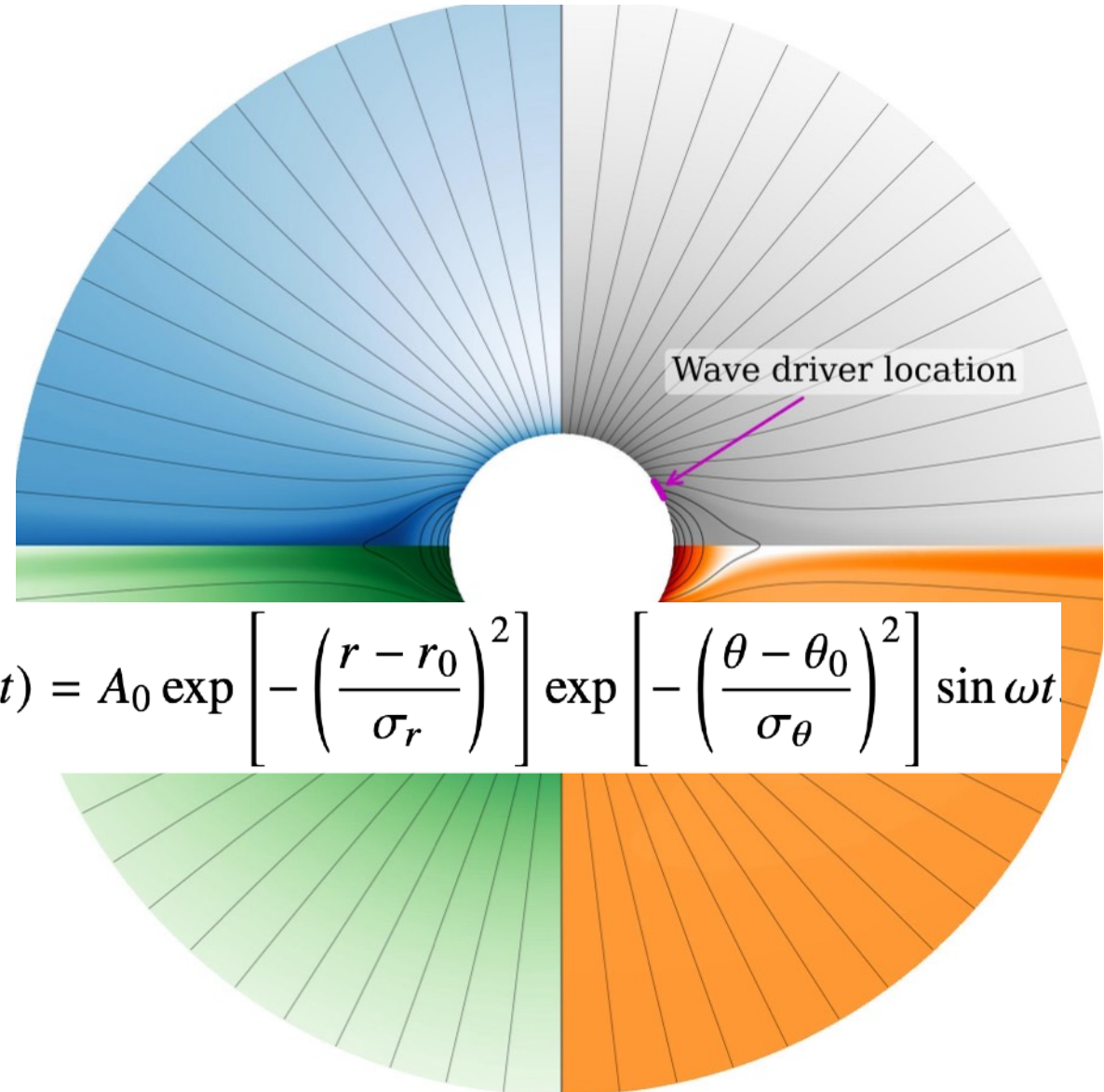
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$$\frac{d}{dt} (\rho \mathbf{v}) = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g} + \rho \mathbf{S}_w(r, \theta, t) + S_w(r, \theta, t) = A_0 \exp \left[-\left(\frac{r - r_0}{\sigma_r} \right)^2 \right] \exp \left[-\left(\frac{\theta - \theta_0}{\sigma_\theta} \right)^2 \right] \sin \omega t$$

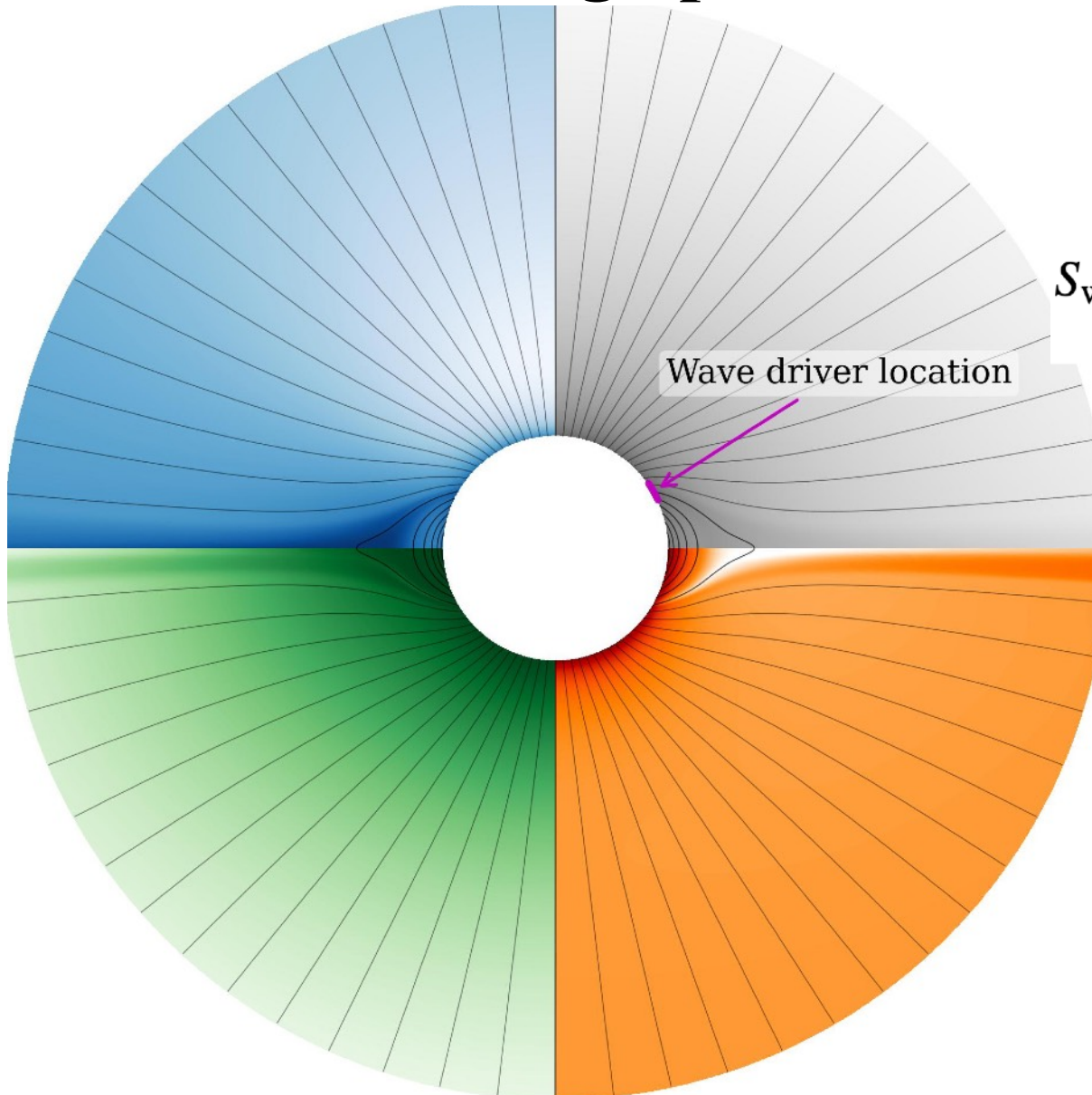
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Setting up a Helmet Streamer: Wave Drivers



$$S_w(r, \theta, t) = A_0 \exp \left[- \left(\frac{r - r_0}{\sigma_r} \right)^2 \right] \exp \left[- \left(\frac{\theta - \theta_0}{\sigma_\theta} \right)^2 \right] \sin \omega t.$$

Alfvén waves: $S_w \parallel \hat{\phi}$

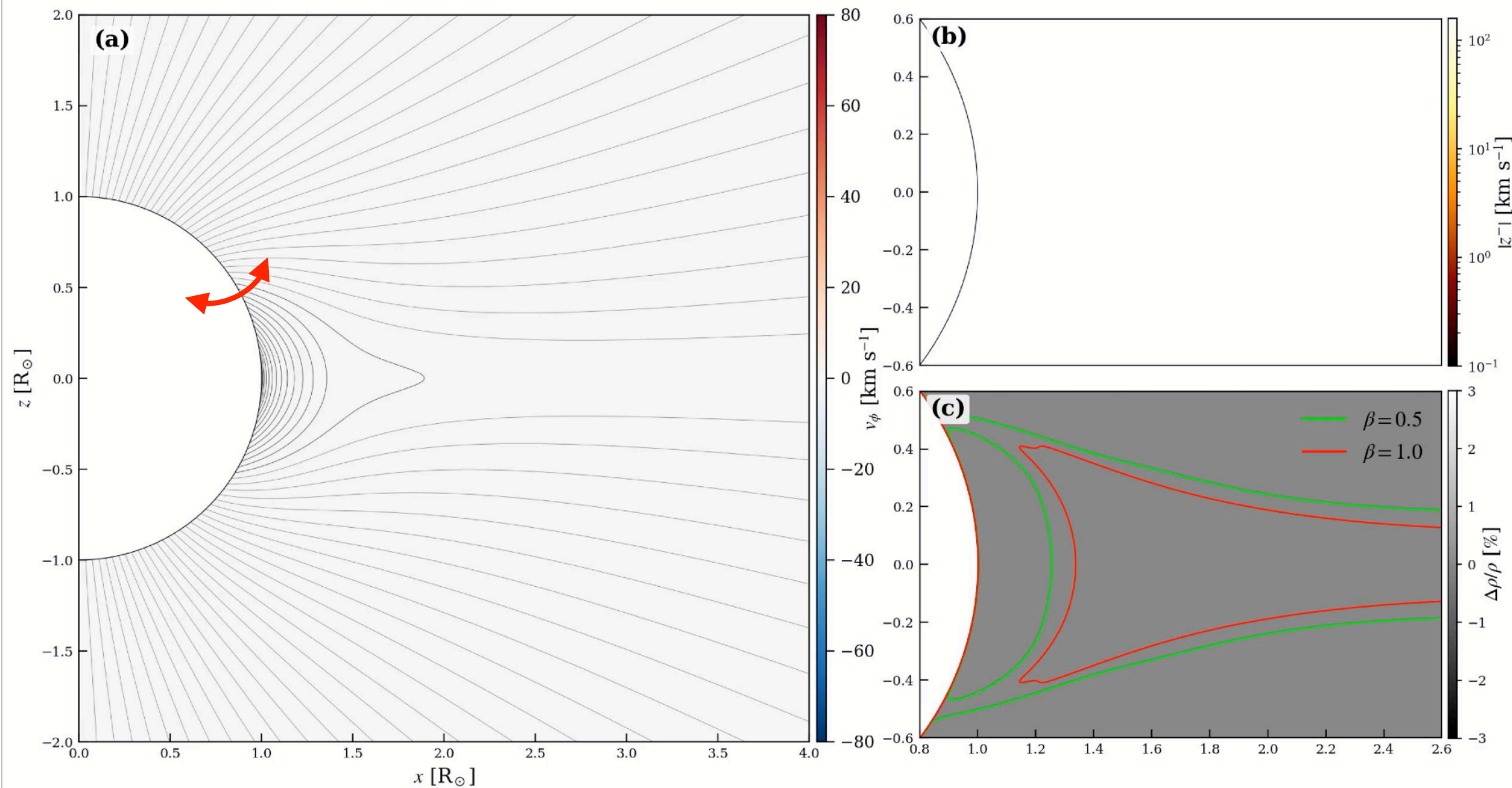
Non-linear effects are seen as compressions via *ponderomotive* forces.

Magnetoacoustic waves: $S_w \parallel \hat{\theta}$

Naturally cause compressions propagating through the medium.

Alfvén Waves in the Streamer

Time: 0.5 (min)

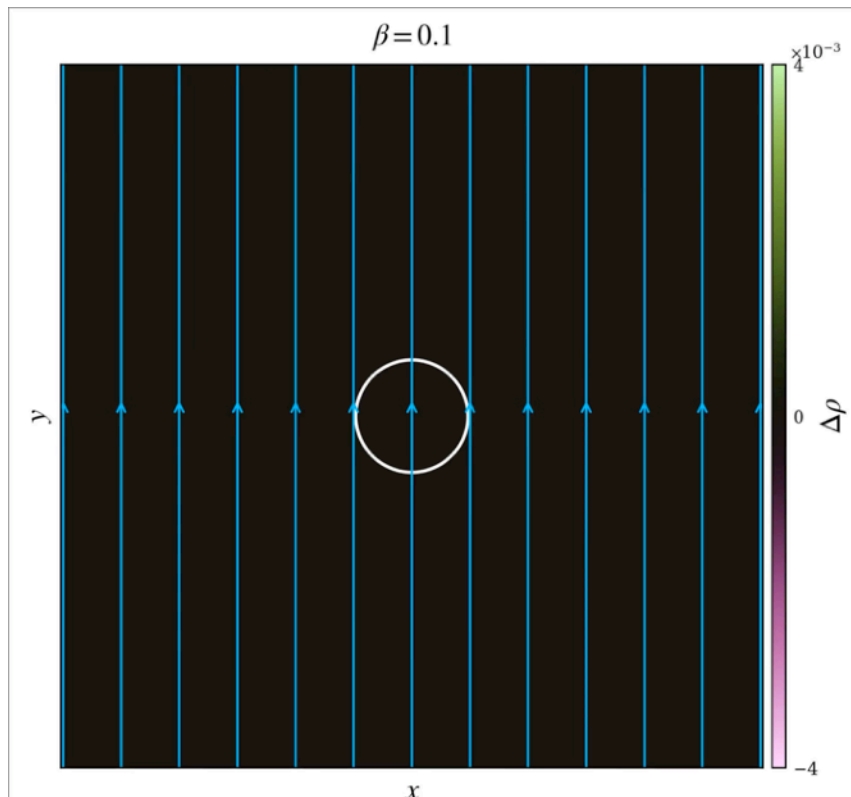


Alfvén Wave Driver: Ponderomotive Effects

$$\frac{d}{dt} (\rho \mathbf{v}) = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g} + \rho S_w (r, \theta, t) \hat{\phi}$$

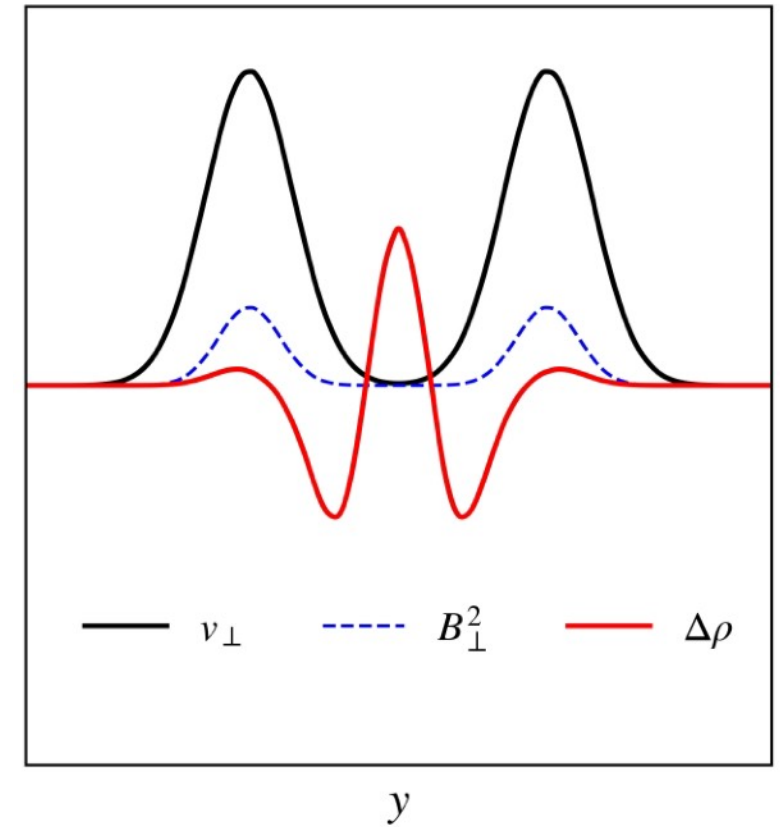
Out of plane perturbations induce plane-parallel flows as the **excess magnetic pressure** releases.

$$\frac{d}{dt} (\rho' \mathbf{v}'_{\parallel}) = -\nabla \left(p' + \frac{B_{\perp}^2}{2\mu_0} \right)$$



A non-linear Alfvén wave train would generally act as a source of slow waves with a doubled frequency.

$\beta = 0.1$

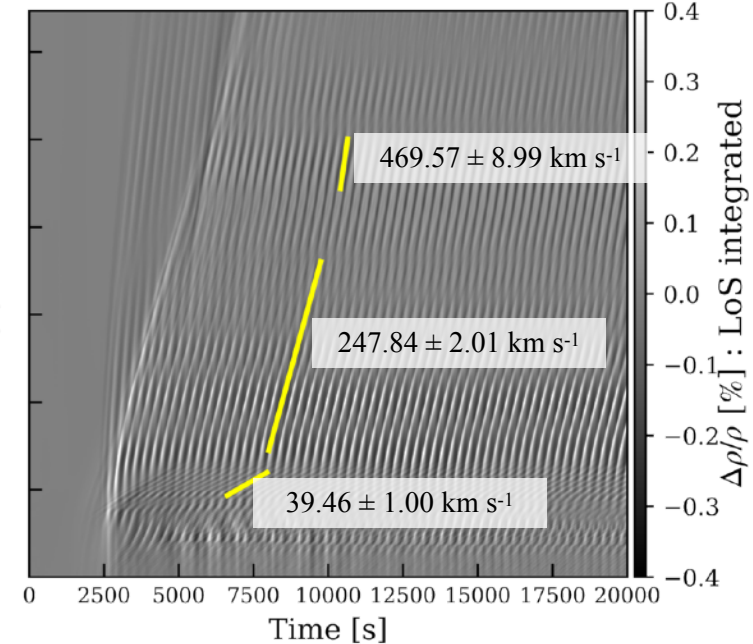
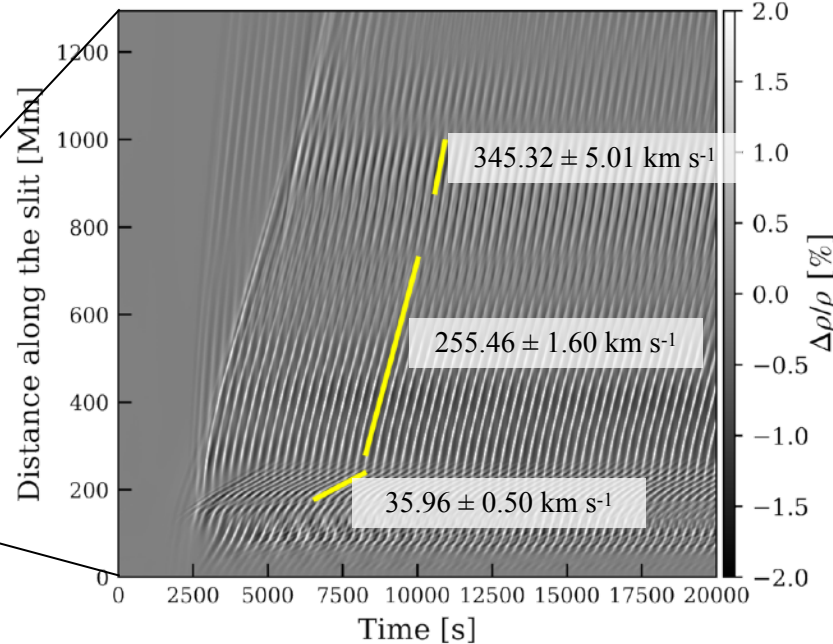
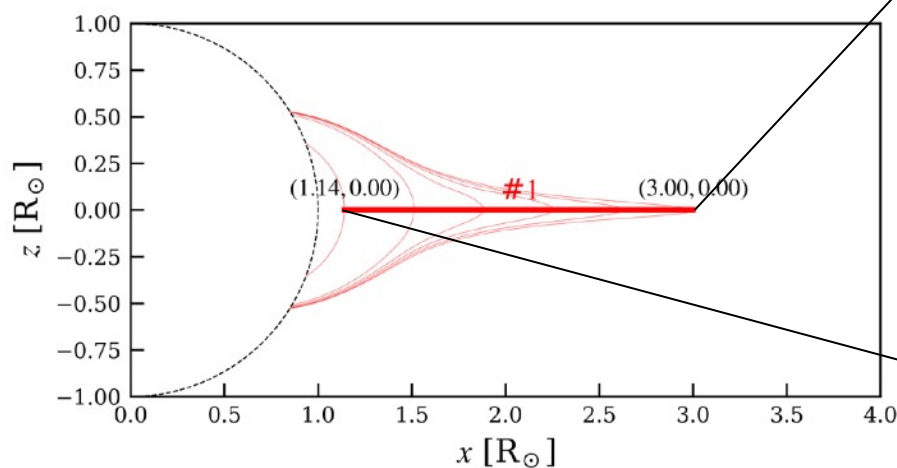
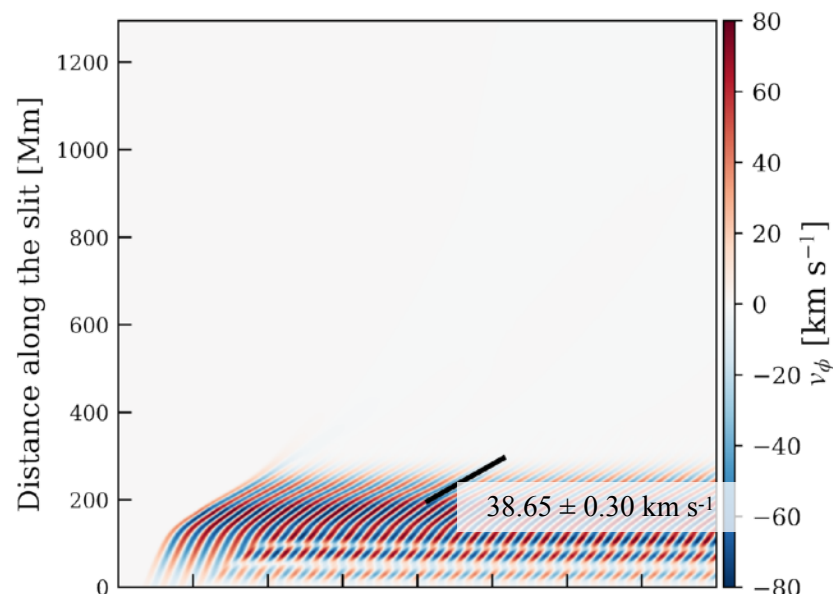
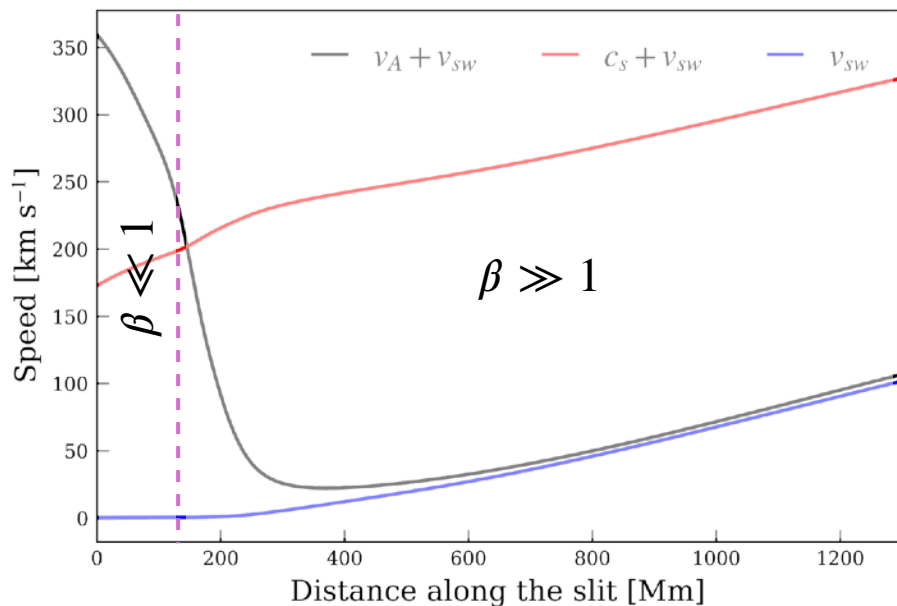


Waves along an Equatorial Slit

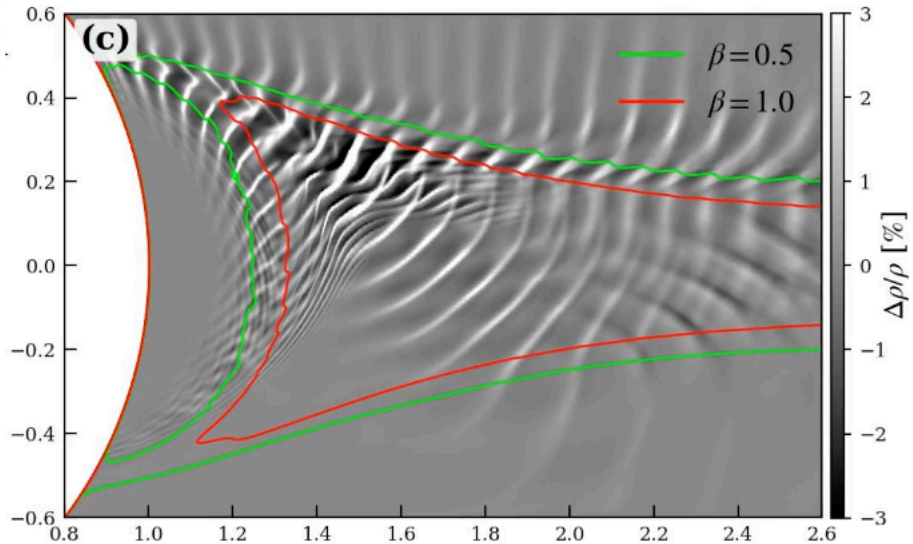
Density fluctuations originate from non-linear Alfvén waves and propagate as magnetoacoustic waves.

Alfvén waves damp after ~ 300 Mm, but density fluctuations can propagate further

$\sim 2\%$ density fluctuations result in $\sim 0.5\%$ LoS intensity variations (assuming azimuthal symmetry).

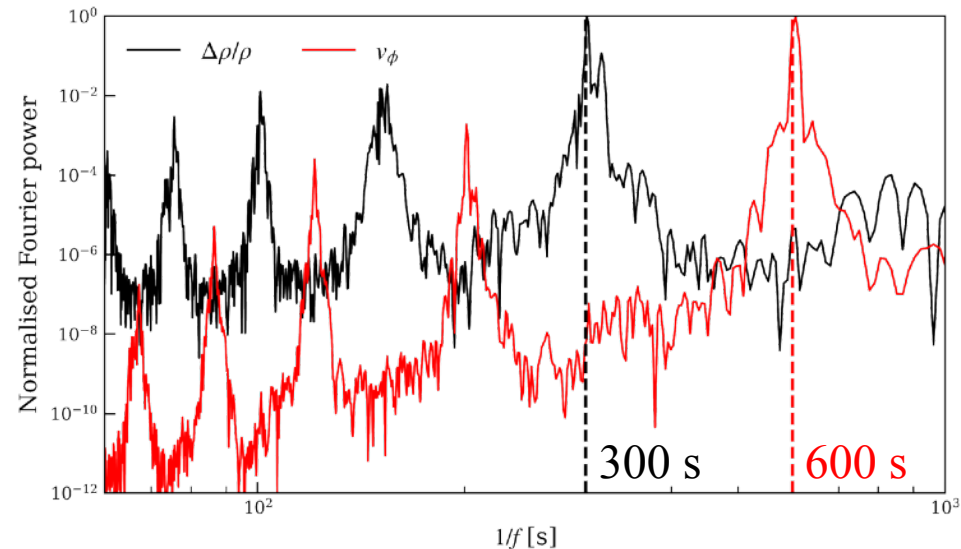
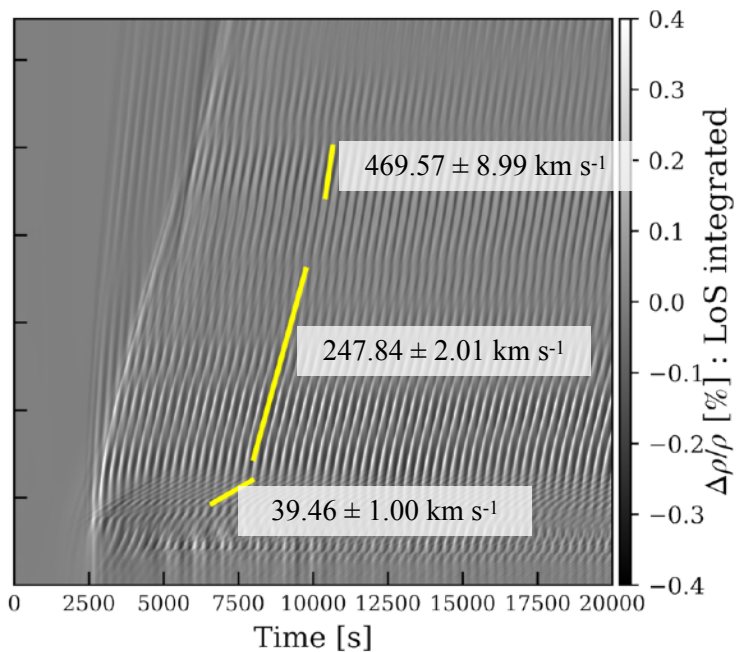
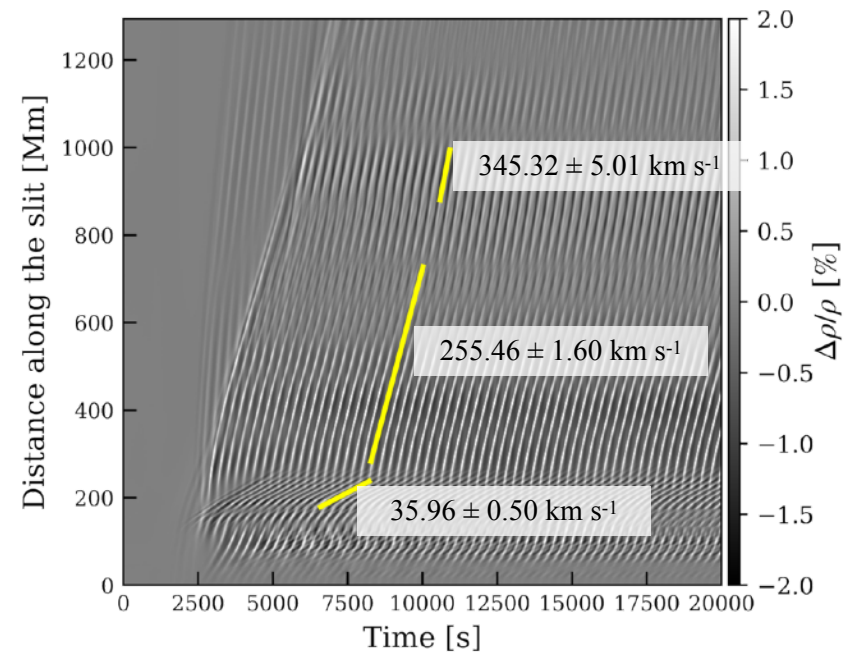


Waves along an Equatorial Slit



Magnetic field lines affect the propagation of density fluctuations. Thus, the time-distance maps only denote wave arrival at those locations.

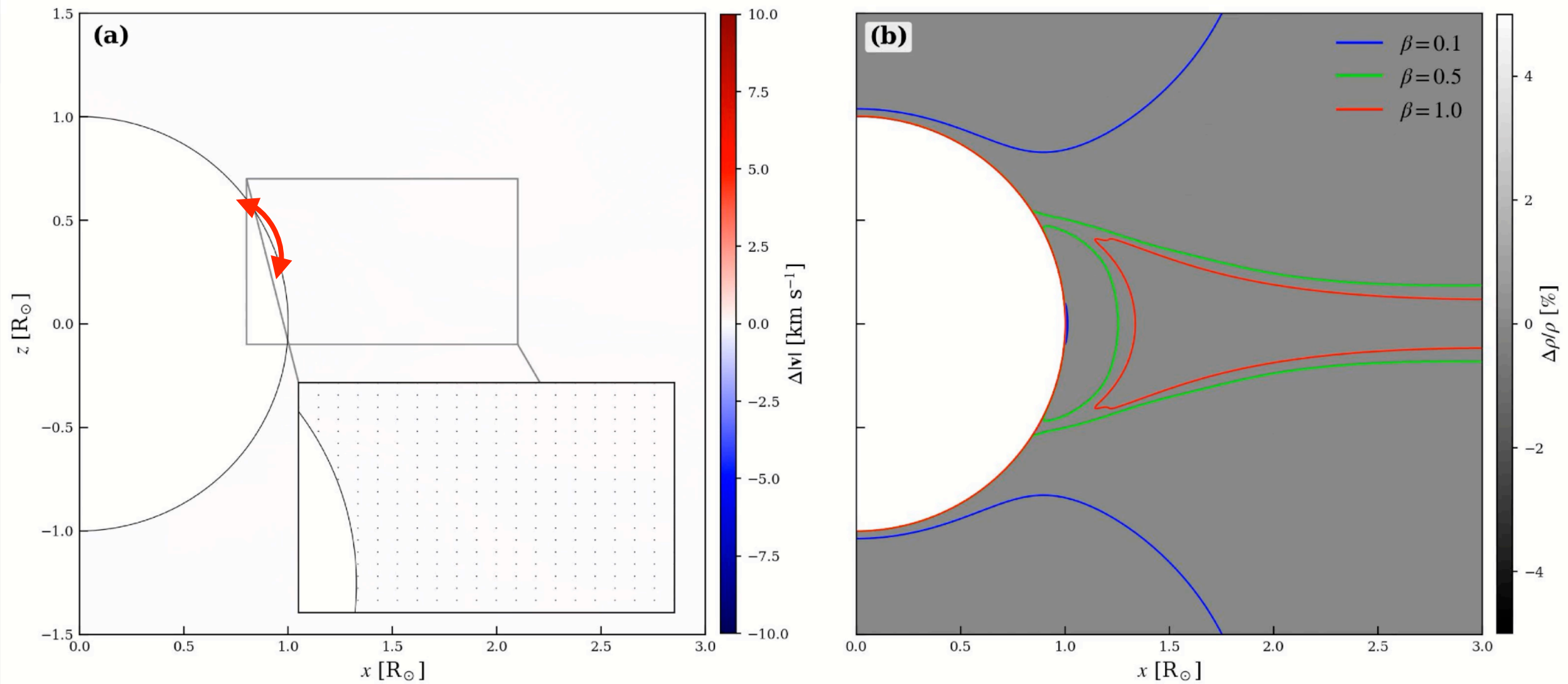
Density fluctuations propagate isotropically in the high β regime, at (approximately) the sound speed.



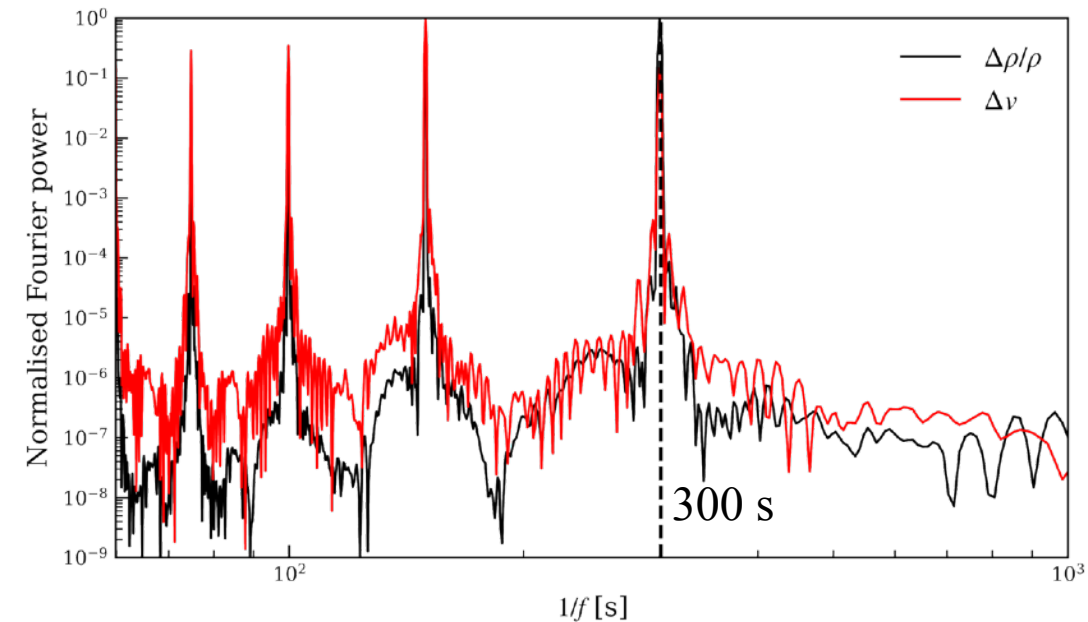
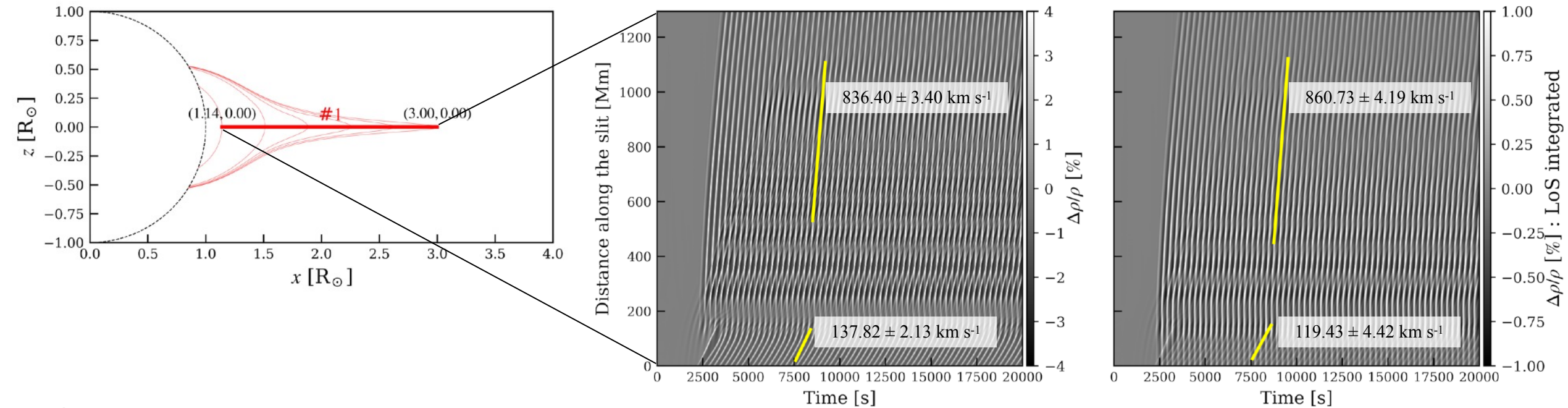
For the density perturbations, maximum Fourier power occurs at half the Alfvén wave period.

Magnetoacoustic Driver

Time: 0.5 (min)



Waves along an Equatorial Slit

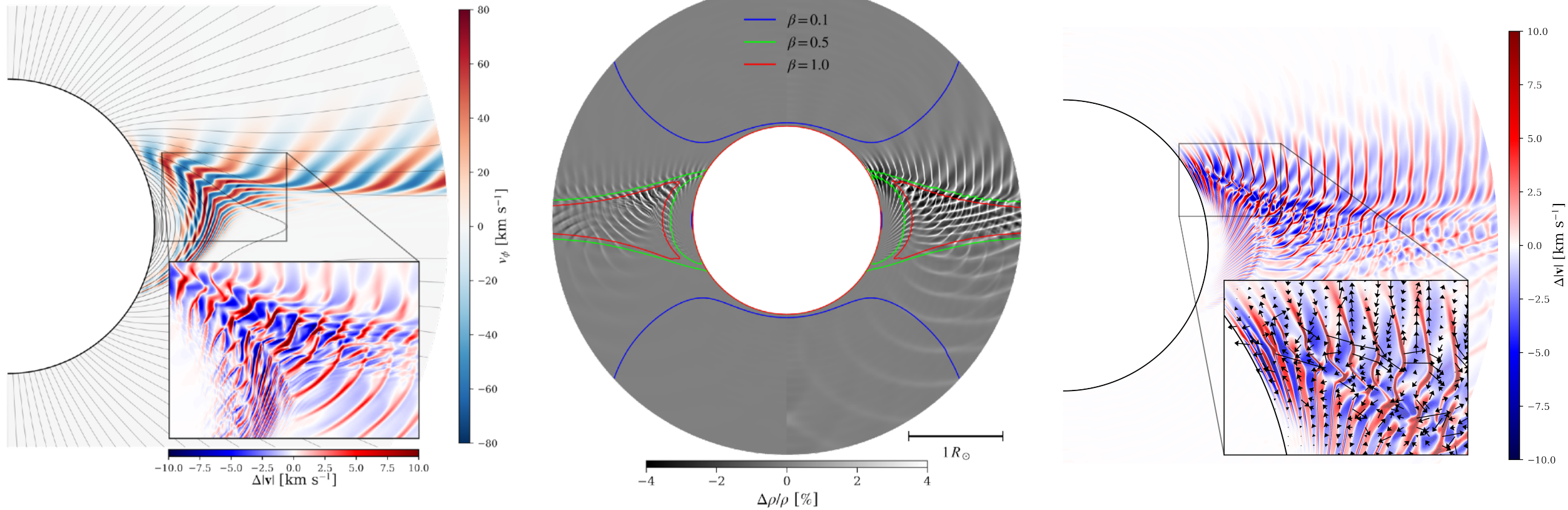


Compressive wave modes

Once generated, density fluctuations propagate similar to those due to the Alfvén wave driver.

Subsequent peaks in the Fourier spectra, but narrower than the case of Alfvén driver where non-linear effects dominate.

Alfvén vs. Magnetoacoustic Driver

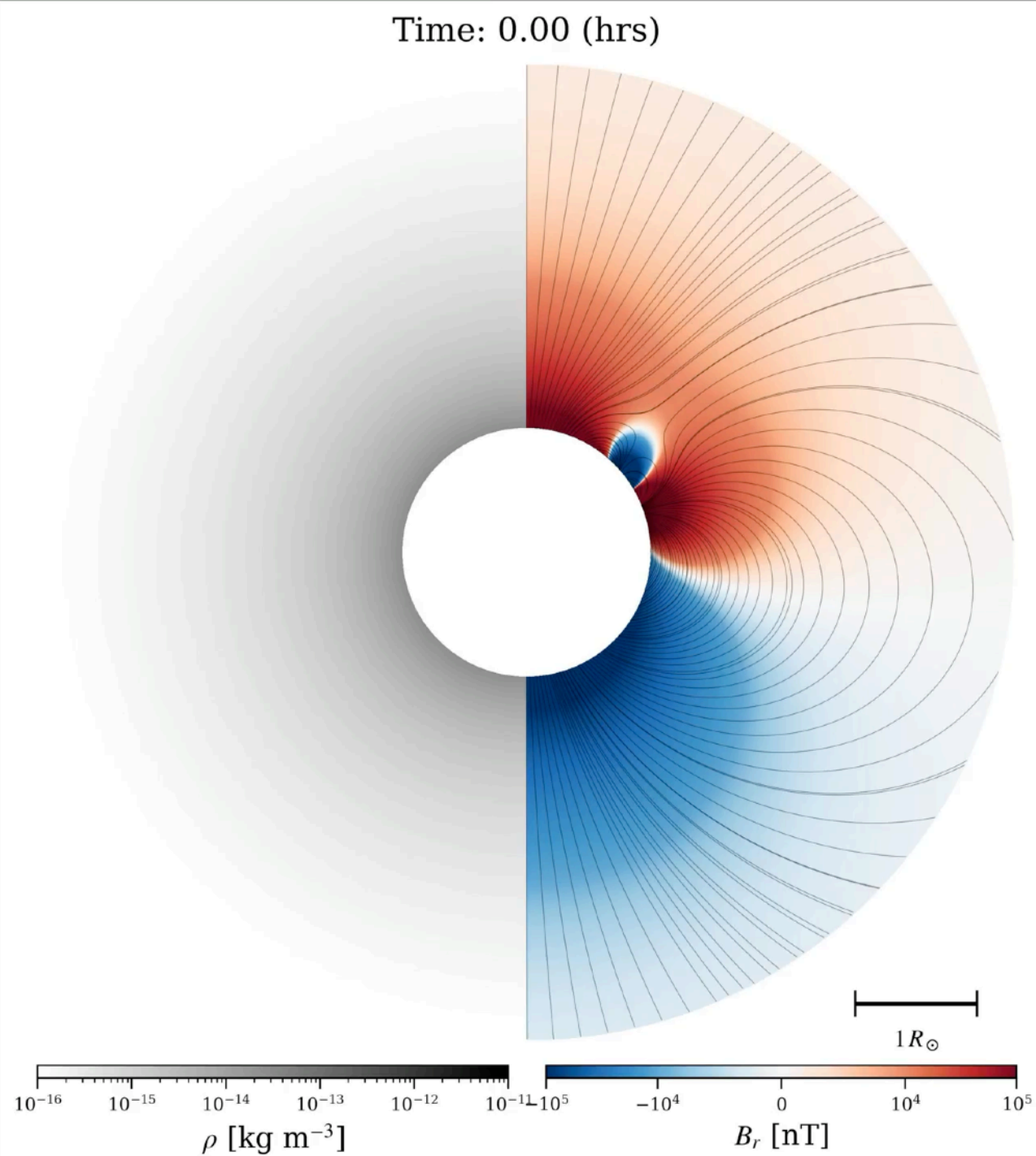


Density fluctuations seen in Metis observations may be produced from non-linear Alfvén and/or magnetoacoustic waves.

Doubling of the density fluctuation frequency with respect to the Alfvénic fluctuation may be a useful in-situ diagnostic to distinguish driving mechanisms.

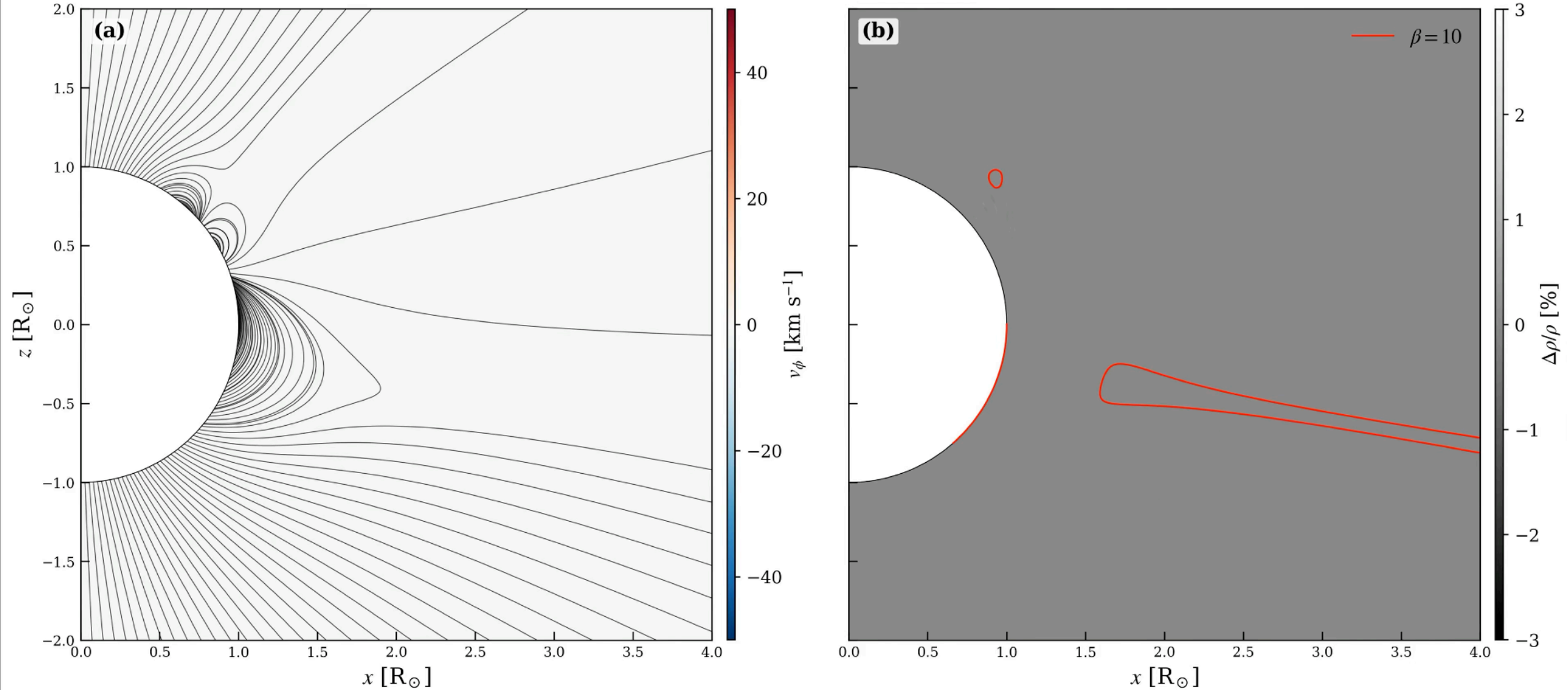
Are there any differences in wave propagation for different magnetic field configurations – helmet streamers vs. pseudo-streamers?

Pseudo-Streamer and Helmet Streamer

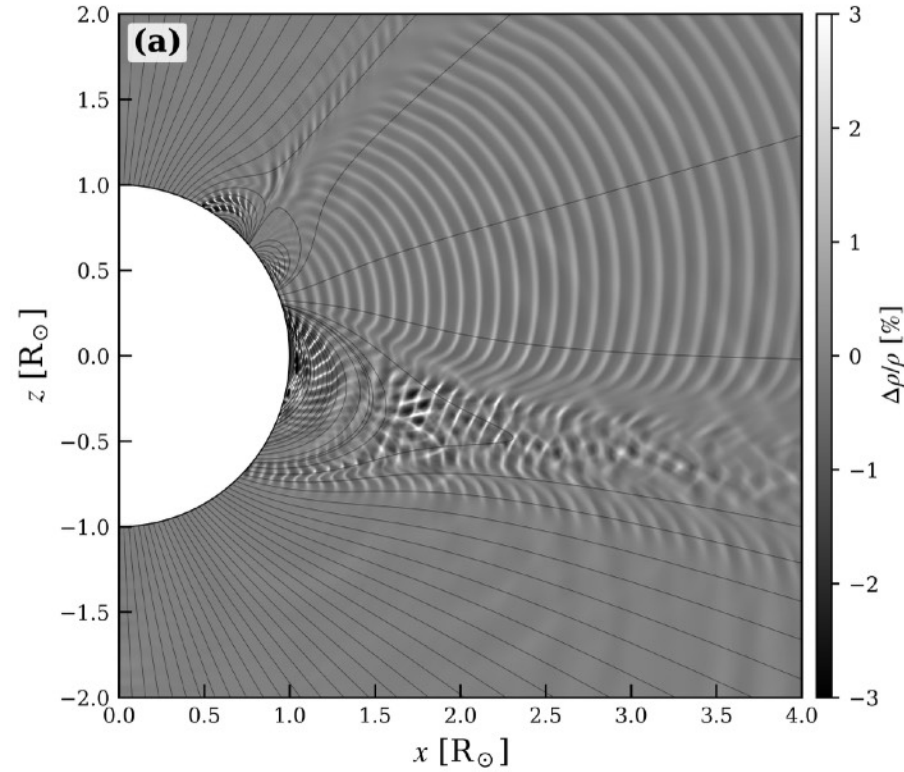


Alfvén Waves between Pseudo-Streamer and Helmet Streamer

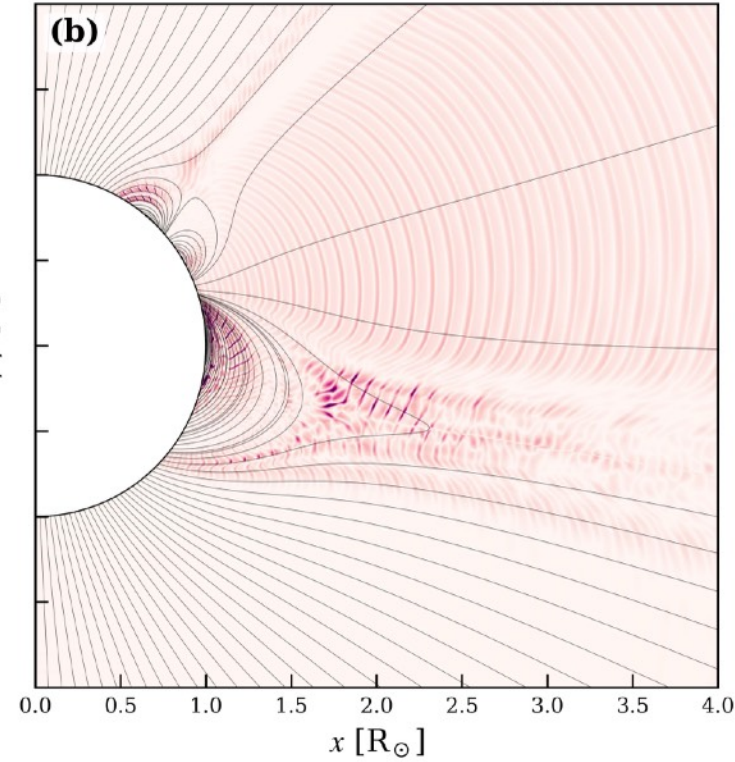
Time: 0.5 (min)



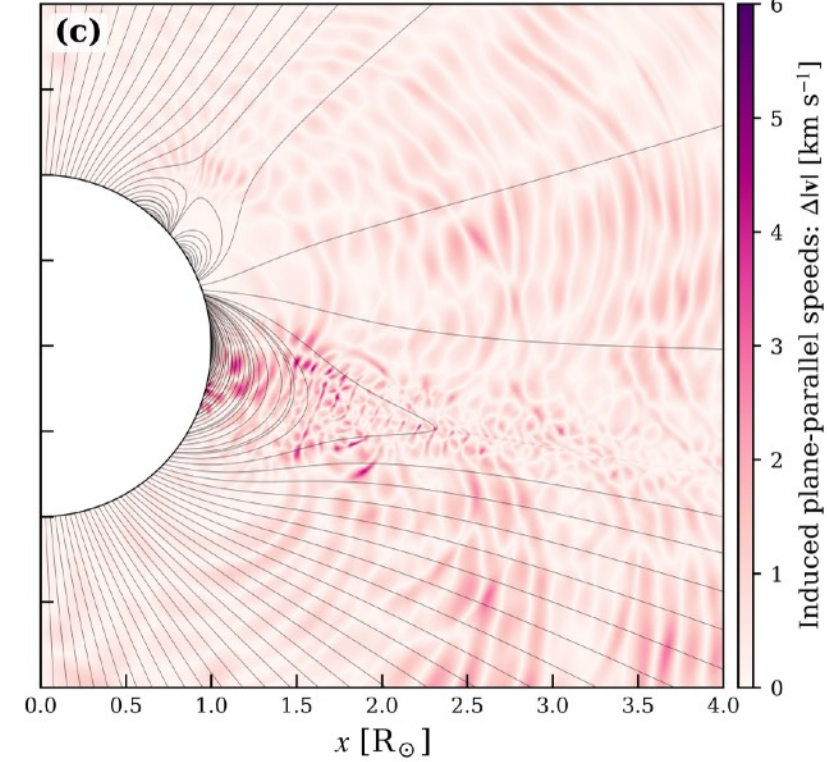
Time: 450.0 (min)



Slow wave component: Δv_{\parallel}



Fast wave component: Δv_{\perp}



High- β region the contribution to density fluctuations is due to both slow and fast modes.

In the low- β region, most of contribution comes from slow modes despite fast modes having a larger spread in the domain.

Because of the magnetic field geometry near the pseudo-streamer, density fluctuations from either side do not cross the separatrix – similar to the behaviour of slow waves. Fast waves can cross the separatrix, but do not contribute significantly to the density fluctuations. However, near the null point, there is contribution from both slow and fast waves.

Conclusions

- Non-linear Alfvén and magnetoacoustic wave modes can produce density fluctuations in the solar atmosphere.
- Due to the ponderomotive effects associated with non-linear Alfvén waves, the density fluctuation periodicity becomes half of the injected Alfvén waves.
- Density fluctuations in both drivers subsequently produce magnetoacoustic waves which propagate at similar speeds along different slit probes.
- The propagation speeds and density contrast are consistent with those observed by SolO/Metis.

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