On the origin of the 1/f spectrum in the solar wind

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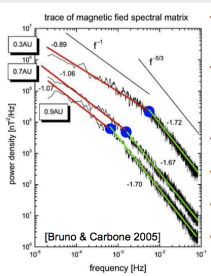
Introduction

Aim: building the low-frequency (1/f) spectrum observed in the solar wind
Method: couple an MHD turbulence model with a model of solar wind
Results: the coupling of the upward and downward Alfvén waves builds a mixed weak & strong turbulence which generates a $k_\perp^{-5/3}$ spectrum together with a 1/f spectrum for the largest eddies which could be at the origin of the 1/f spectrum observed at larger distances

The low-frequency magnetic spectrum

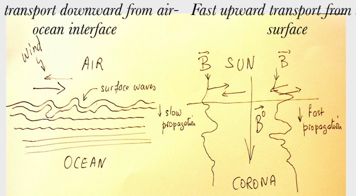
The break between the f^{-1} and $f^{-5/3}$ range is thought to mark the boundary between the large scales dominated by expansion and the smaller scales dominated by nonlinear coupling (*Tu et al 1984*)



The 1/f range thus seems to be a fossil remnant with its origin being controversial:
- Image of the photospheric spectrum [*Matthaeus et al 2007*]
- MHD turbulence [*Dmitruk et al 2009*]
- Coronal spectrum [*Close et al. 2004*]
- Partial trapping in the subaslfvénic region [*Hollweg & Isenberg 2007*]
- Strong coupling in the subalfvénic wind (*Velli Grappin Mangeney 1989*)

MHD with mean field B°

Slow transport downward from air-ocean interface — *Fast upward transport from solar surface*



Homogeneous turbulence

Physical/Numerical model

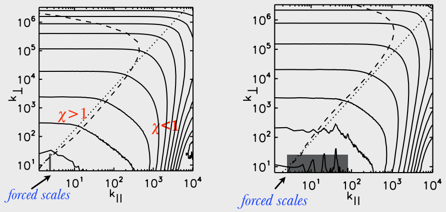
1. Reduced MHD ($b/B° << 1$)
- No gradients // B° (x) except for linear propagation (B°.∇)
- No parallel comp. ($b_{//}=u_{//}=0$), •Incompressible limit ($\nabla_\perp.b_\perp=\nabla_\perp.u_\perp=0$)

=> Quasi 2D, but still b,u depend on x

Two regimes (initial conditions or forcing):
- WEAK if $B°.\nabla >> b_\perp.\nabla_\perp$ => no // cascade, $E(k_\perp) \propto k_\perp^{-2}$
- STRONG if $B°.\nabla \approx b_\perp.\nabla_\perp$ => $E(k_\perp) \propto k_\perp^{-5/3}$, $E(k_{//}) \propto k_{//}^{-2}$

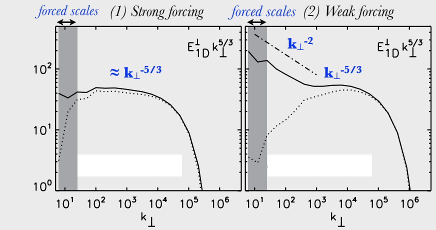
2. Shell Reduced MHD
- solves for $\hat{\mathbf{u}}(\mathbf{x},\mathbf{k}_\perp)$ (1/2 FFT) (one wavenumber per "shell" $k_\perp=2^n k°$)
- allows reaching $Re \approx 10^6$

Strong and weak forcing: 3D spectrum



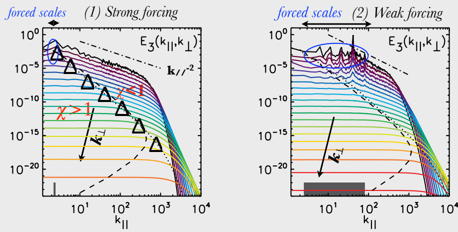
Dashed : $\chi = 1$ isocontour; *dotted*: theoretical $\chi = 1$ isocontour

Reduced ⊥ energy spectrum $E(k_\perp)$



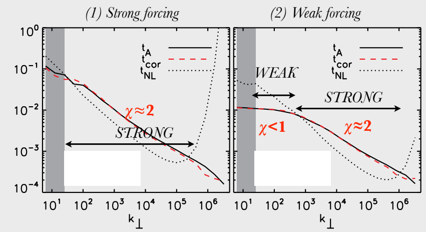
Dotted: reduced spectra obtained from 3D spectra after suppressing excitation in region $\chi<1/2 \Rightarrow$ suppresses $k_\perp^{-2}$ weak scaling (right)

Strong and weak forcing: $k_{//}^{-m}$ tails



- Energy in $\chi < 1$ region : $\mathbf{E_3}(k_\perp,k_{//}) \propto \mathbf{k_{//}^{-n}}$ due to $1/f^n$ spectrum of large ⊥ eddies
- Δ *marks boundary* of "strong" regime $\Delta f = 1/t_{cor}(k_\perp) = 1/t_{NL} = kz^\pm$

Time scale diagnostics $\chi = kz^-/k_{//}B°$



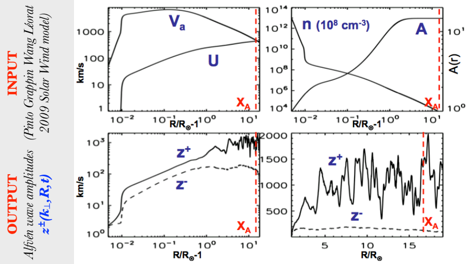
Solar Wind turbulence

Physical/Numerical model (solar wind case)

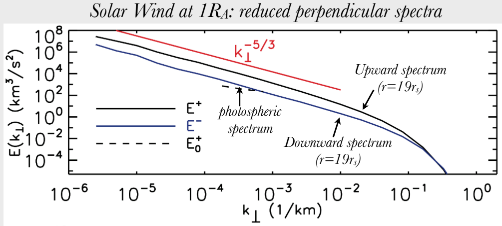
1. Numerical model
- Choose a (numerical) 1D (radial) *stationary wind solution* (solving energy equations etc...) U, B, n, V_a
- Use *Shell-Reduced MHD* + *variable phase speed* U±Va *including expansion weakening* on perp. gradients

2. New physics
- Stratification ; z+ >> z- (imbalanced turbulence)

Snapshots: from surface to Alfvén radius (≈ 19R_s)



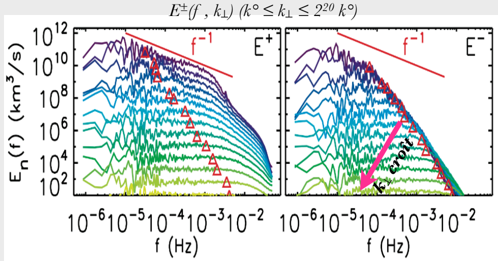
Solar Wind at 1R_A: reduced perpendicular spectra



- Both upward and downward spectra $\propto k_\perp^{-5/3}$
- Large imbalance (weak reflection): $E^- \approx E^+/10 \Rightarrow t_{NL}^+ \propto 1/z- > t_{NL}^- \propto 1/z+$

Solar Wind at 1R_A: the 1/f sound of large eddies

$E^\pm(f, k_\perp)$ $(k° \le k_\perp \le 2^{20} k°)$



- *Strong cascade prediction for E- spectrum:*
$\Delta f \approx 1/T_{cor}(k_\perp) = 1/t_{NL} = kz^\pm \Rightarrow$ LEFT of symbol Δ
- Additional 1/f tail for large z+ eddies

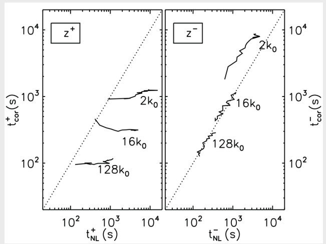
Origin of the frequency spectrum

- $R << R_{Alfvén}$: the absolute frame coincides with the plasma frame, hence the frequency spectrum (as well as the autocorrelation of the signal) reflects
  - either the nonlinear clock of eddies (strong regime)
  - or a shorter time (weak turbulence)
  - or shorter times scales of smaller eddies
- $R \approx R_{Alfvén}$: the frequency spectrum reflects partially the internal clock of the eddies AND the parallel spatial structure of the signal

Diagnostics of weak and strong turbulence

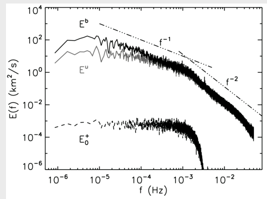
Figure below shows that
- for the major upward species z+ the cascade is weak (and becomes weaker as distance increases)
- for z- the cascade is strong

Correlation time/ NL time 1.2<R/Rs<19



Conclusion

Time diagnostics shows that in the subalfvénic region the upward wave suffers weak coupling, while the downard wave suffers strong coupling.
However, probably due to the recycling of downward into upward waves at the transition region, both wave species show a perpendicular "strong" spectrum $\propto k_\perp^{-5/3}$.
At the Alfvén point the integrated spectrum of the dominant component (z+ or b) *scales as 1/f* at low f (figure below)
How evolves the 1/f spectrum at increasing R ?
NB The S-RMHD model cannot explore this, since <B> *has to be radial*



As B° rotates (Parker spiral) the k_r^{-1} law may become the observed f^{-1}.
We are presently checking this hypothesis using the Expanding Box Model (3D MHD with comobile coordinates)
(*Grappin Velli Mangeney 1993*)