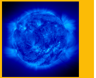

Alfvénic turbulence and the acceleration of the fast solar wind

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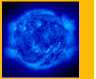


Observations in the Heliosphere

- Strong correlation between *u* and *b* fluctuations at 1 AU

  `[Belcher & Davis 1977]`

- Alfvén waves are ubiquitous in the fast solar wind, with $Z^+ >> Z^-$
- The turbulent spectrum evolves with distance, showing different power-law scalings at low (-1) and high (-5/3) frequencies

  `[Bavassano et al., 1982, Tu et al. 1984, Bavassano & Smith 1986]`

- Decay of fluctuation energy ($e^+ = |Z^+|^2/4$) with distance is faster than $\propto R^{-1}$ (WKB)

  `[Bavassano et al. 2000]`

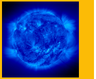
- Wind temperature decays less than adiabatic ($\propto R^{-4/3}$)

  `[Ulysses]`

Elsässer variables

$$\mathbf{Z}^\pm = \mathbf{u} \mp sign(\mathbf{B})\mathbf{b}/\sqrt{4\pi\rho}$$

- Alfvénic turbulence has a solar origin
- Not a simple decaying turbulence
- Turbulence is active in the solar wind

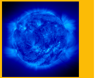


Solar wind models, a synopsis

Solar wind models with Alfvén waves as source of pressure `[Alazraki and Couturier, 1971]` and/or heating: waves are launched at the "base" (photosphere - corona)

- Prescribe a damping length to dissipate the wave energy **`[Wang 1993, MacGregor & Charbonneau 1999, Hansteen et al. 1999, Li 2003, Lie-Svendsen et al. 2003]`**
- Postulate a turbulent cascade **`[Isenberg & Hollweg 1982, Tu et al 1984, Li et al. 1999, Hu et al. 2000, Li 2003, Isenberg 2004]`**
- Postulate a wide spectrum of AW **`[Suzuki & Inutsuka 2006]`** or use a simplified model for the turbulent dissipation **`[Cranmer et al. 2007]`**

How efficient is reflection in producing a turbulent cascade? What do turbulent heating profiles look like?

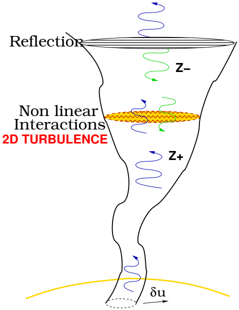


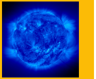
The model

Reflection Driven Turbulence

- Waves are launched from the base of the corona
- Reflection: large scale gradients (background wind) produce downward propagating waves
- Turbulence: nonlinear interactions are triggered,
- Dissipation: energy flows down toward small scales in $\perp$ planes, where resistivity & viscosity are no more negligible

`[Velli et al., 1989, Matthaeus et al.1999, Dmitruk et al. 2001, 2002, 2003]` for a static atmosphere

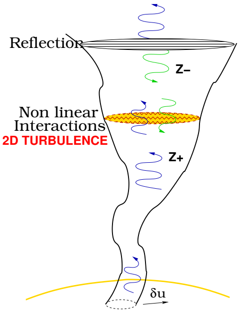


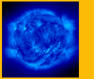


The model

Basic assumptions

- Incompressible MHD equations, radial propagation
- Specified 1D solar wind model (up to 17 $R_\odot$), with non uniform density (non WKB)
- 2D Shell model accounts for nonlinear interactions (High Reynolds numbers)
- Open boundaries at the bottom and at the top of the domain
- Force at large scales with a time-correlated function of period T





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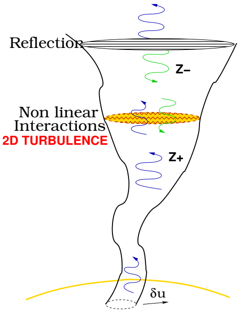
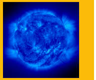


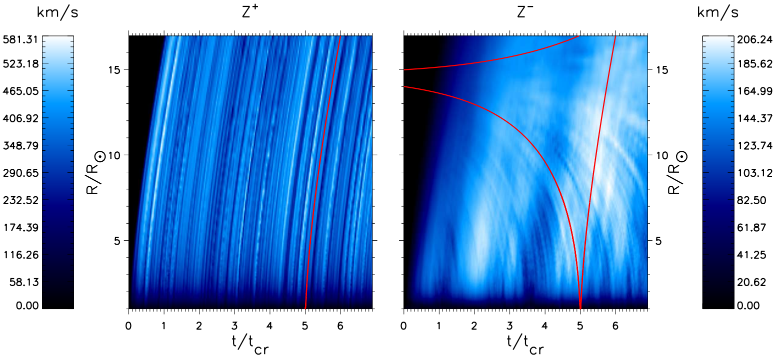
Need for a parametric study $(\omega,\ \delta u)$

- **Reflection** distributes energy among the conterpropagating waves
  → depends on the **wave frequency**
- **NL interactions** transfer the energy to small scales
  → depend on the **wave amplitude**

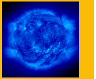
$400\ \mathrm{s} < T < 10000\ \mathrm{s}$ $\quad$ $28\ \mathrm{km/s} < \delta u_\odot < 53\ \mathrm{km/s}$



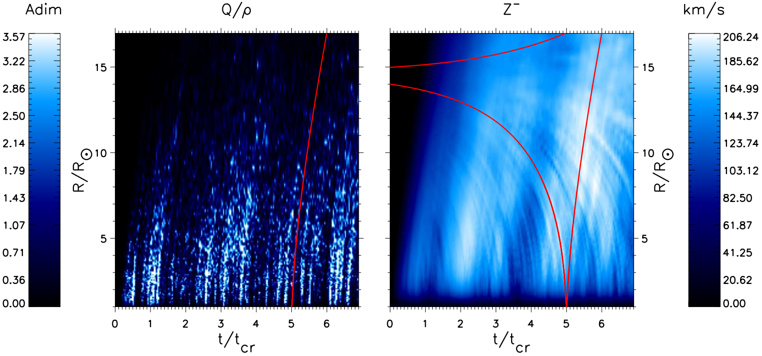
Reflection



- Reflected waves propagate inwards and outwards (the latter maintainig the phase of the mother wave) `[Velli et al.1989, Isenberg & Hollweg 2007]`
- The heating per unit mass follows the outward propagation path



Reflection



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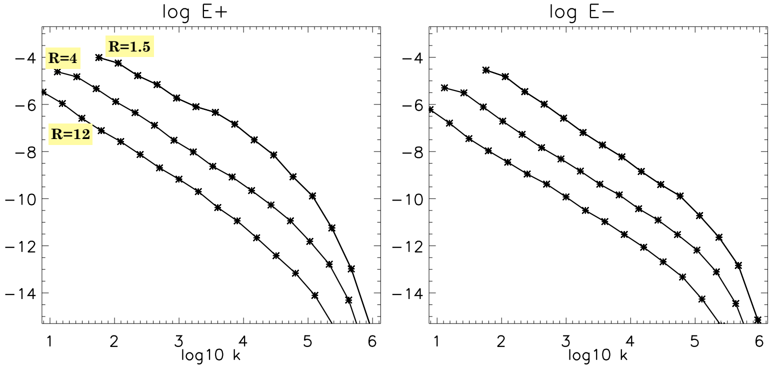
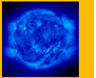
Perpendicular spectra

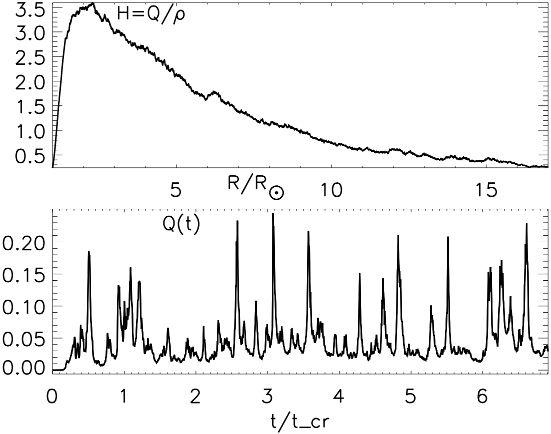


Not a “standard” turbulence

- The cascade is imbalanced $E^- < E^+$
- The E^+ spectra show a break in the spectral slope
- The slopes evolve with distance



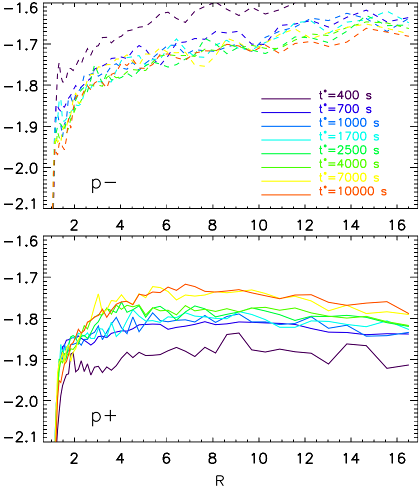
The heating function

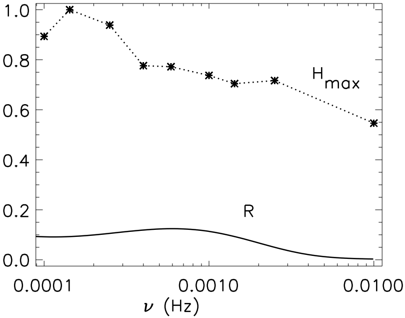


- Turbulence develops in short time scales
- H_{max} is close to the coronal base

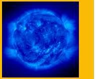
Dependence on ω

Spectral slope vs $R_\odot$



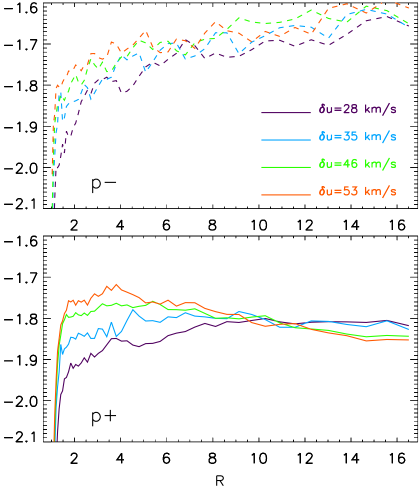


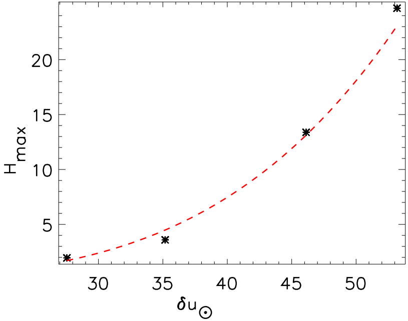
- The cascade is more "balanced"
- $H_{max} \propto$ reflection coefficient



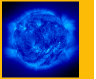
Dependence on $\delta u_\odot$

Spectral slope vs $R_\odot$





- The nonlinear terms become more and more important with respect to the propagation effects.
- $H_{max} \propto (\delta u_\odot)^4$



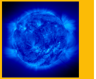
Retrieving the dissipation profile

The viscous damping of the energy carried by the waves is given by

$$\frac{Q}{\rho} = \nu \boldsymbol{\nabla}^2 \left(E^+ + E^-\right) = \nu k^2 \left(E^+ + E^-\right)$$

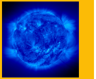
for a turbulent medium it acts at small (dissipative) scales. Assuming a power-law spectrum with indexes $p^\pm$ one gets:

$$\frac{Q}{\rho} = \nu k_\nu^2 \left[E_0^+(r) \left(\frac{k_\nu}{k_0}\right)^{-p^+ +1} + E_0^-(r) \left(\frac{k_\nu}{k_0}\right)^{-p^- +1} \right]$$



Retrieving the dissipation profile

$$\frac{Q}{\rho} \propto \nu k_\nu^2 \left[E_0^+(r) \left(\frac{k_\nu}{k_0}\right)^{-p^+ +1} + E_0^-(r) \left(\frac{k_\nu}{k_0}\right)^{-p^- +1} \right]$$



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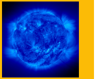
$$\frac{Q}{\rho} \propto \nu k_\nu^2 \left[E_0^+(r) \left(\frac{k_\nu}{k_0}\right)^{-p^+ +1} + E_0^-(r) \left(\frac{k_\nu}{k_0}\right)^{-p^- +1} \right]$$

For low frequency waves

$$E_0^+(r) = \left(f^+ Z_\odot^+ + f^- Z_\odot^-\right)^2$$
$$E_0^-(r) = \left(f^- Z_\odot^+ + f^+ Z_\odot^-\right)^2$$

where $f^\pm = \sqrt{\frac{M_a}{M_{a\odot}}} \frac{M_{a\odot} \pm 1}{M_a \pm 1}$ depend only on the atmosphere

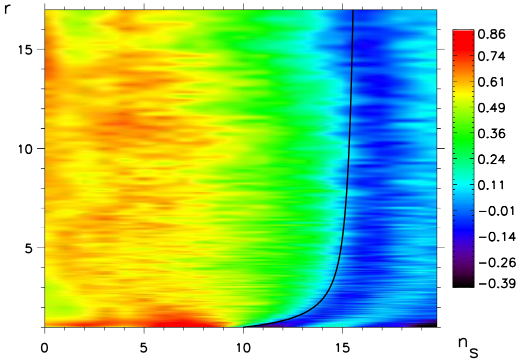
and $Z_\odot^\pm$ are values at the base of the corona



Retrieving the dissipation profile

$$\frac{Q}{\rho} \propto \nu k_\nu^2 \left[E_0^+(r) \left(\frac{k_\nu}{k_0}\right)^{-p^+ +1} + E_0^-(r) \left(\frac{k_\nu}{k_0}\right)^{-p^- +1} \right]$$

contour of σ_c: n_{shell} vs $R_\odot$



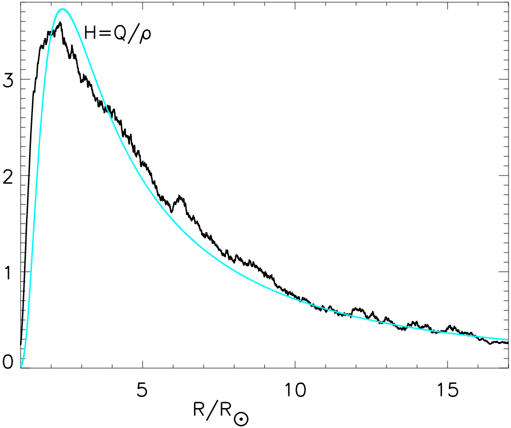
$$\sigma_c = \frac{E^+ - E^-}{E^+ + E^-}$$

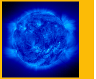
$$k(r) = k_0 / \sqrt{A(r)}$$

$$k_\nu(r) = k_0 \left(\frac{E_0^\mp}{\nu^2 k^2} \right)^{\frac{1}{p^\pm +}}$$

Retrieving the dissipation profile

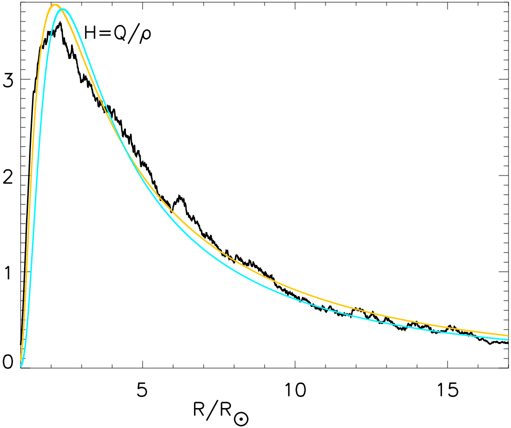
$$\frac{Q}{\rho} \propto \nu k_\nu^2 \left[E_0^+(r) \left(\frac{k_\nu}{k_0}\right)^{-p^+ +1} + E_0^-(r) \left(\frac{k_\nu}{k_0}\right)^{-p^- +1} \right]$$

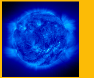




Retrieving the dissipation profile

$$\frac{Q}{\rho} = \alpha_0 \frac{M_a}{(M_a+1)^2} \frac{V_a^{\alpha_1}}{\sqrt{A}} \qquad \alpha_0 = 0.076,\ \alpha_1 = 0.79$$





Conclusions

- Reflection driven turbulence :
- Develops in a wide range of conditions $(\omega,\ \delta u_\odot)$
- Develops in short time scales (smaller than the propagation time scale)
- The heating function peaks around the sonic critical point
- Can be a competitive mechanism with respect to wave coupling & shock dissipation (e.g. `[Suzuki & Inutsuka 2006]`)
- Reflection driven turbulence is not standard (imbalanced: different fluxes and spectral slopes for outgoing and ingoing components)
- Based on scaling laws from sims one can contruct heating functions which depend on only few parameters: the large scale fields $(U,\ V_a)$ and observables $(\delta u_\odot)$
- Fit parametrical dependence can be used in more complex solar wind model to include turbulent heating