A Summary of the Evidence in Favor of the Idea that the Solar Wind is Accelerated by Waves and/or Turbulence

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Abstract

Despite more than a half-century of study, the basic physical processes that are responsible for accelerating the solar wind are not known (or at least not universally agreed upon). The mechanism that has been studied the most appears to be the dissipation of waves and turbulent eddies. Roberts (2010) presented a series of arguments why these processes may not be as effective as has been assumed in the past. In this presentation, we attempt to counter these arguments and demonstrate that there may still be hope for the wave/turbulence explanation.

A combination of observational and model-based evidence will be brought to bear in order to show that the most likely strength of Alfvén waves in coronal holes is sufficient to provide both: (1) substantial wave-pressure acceleration in high-speed streams, and (2) sufficient coronal heating, via MHD turbulence seeded by partial reflection, to heat and accelerate open-field regions of the corona that connect to the solar wind.

Can the in situ MHD fluctuations be extrapolated down to the corona with dissipationless WKB theory?

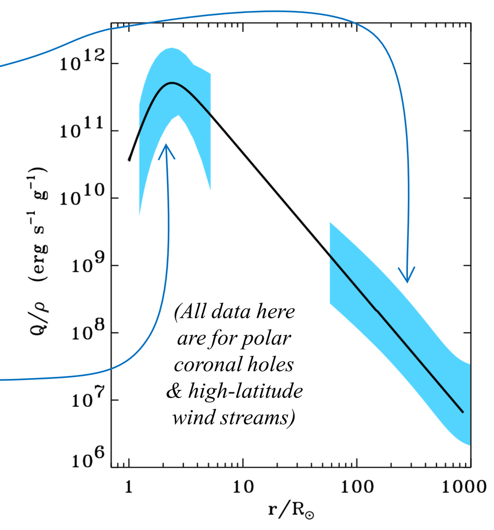
- No. If the turbulence is "reflection-driven," then the WKB approximation fails below the Alfvén critical point (at which $u = V_A$, around $r \approx$ 10–20 R_s).
- Dmitruk et al. (2002), Chandran & Hollweg (2009), and others, showed that the **outward**-propagating waves cascade on a "slow" time scale ($\tau_{\rm casc}$) driven by the local amplitude of **inward**-propagating waves.
- How does the cascade time scale compare with the time taken for outward-propagating waves to simply **propagate out** a distance r ($\tau_{\rm out}$)?

$$\tau_{\rm casc} = \frac{\lambda_\perp}{Z_{\rm in}} \approx \left(\frac{\partial V_A}{\partial r}\right)^{-1} \qquad \tau_{\rm out} = \frac{r}{u + V_A}$$

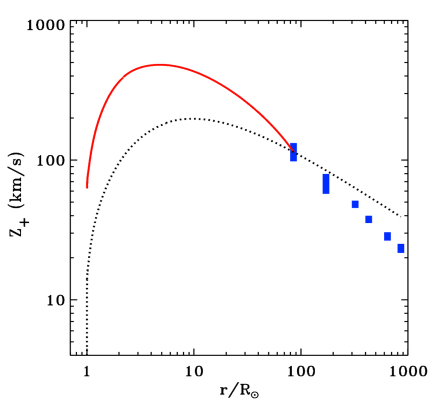
- In the heliosphere, $\tau_{\rm out} \ll \tau_{\rm casc}$, i.e., cascade is slower than propagation. The wave spectrum is likely to be "frozen" (see also Grappin et al. 1993), and thus WKB-type extrapolations may be okay.
- In the corona (below the Alfvén critical point), $\tau_{\rm out} \approx \tau_{\rm casc}$, i.e., cascade competes with propagation, and the wave spectrum is likely to still be evolving rapidly & nonlinearly. The WKB approximation breaks down.

Are the MHD fluctuations undergoing turbulent cascade & dissipation?

- Probably. A large amount of evidence exists to support the idea that turbulence is actively dissipating in interplanetary space (r > 0.3 AU).
- Velli et al. (1989) and Verdini et al. (2009) found that, for reflection-driven turbulence, a cascade can coexist with a shallow power spectrum (k^{-1} to $k^{-1.2}$).
- The local **turbulent dissipation rate** can be estimated from the statistical properties of measured fluctuations (see, e.g., Verma et al. 1995; Matthaeus et al. 1999b; MacBride et al. 2008; Marino et al. 2008; Stawarz et al. 2010).
- Independently, the *in situ* **plasma heating rate** can be estimated from the radial evolution of the plasma's thermal energy (see, e.g., Freeman 1988; Vasquez et al. 2007; Cranmer et al. 2009).
- Studies of both processes often show that the heating rate ≈ the expected dissipation rate (Breech et al. 2009).
- Also, empirical studies of solar wind acceleration have helped to constrain the amount of coronal heating that must exist over the first few solar radii above the surface (see, e.g., Cranmer 2004).
- We have fit these **observationally constrained heating rates** with a simple function (black curve).



- Assuming energy conservation, gradual heating must correspond to gradual wave dissipation. We can estimate how much relative dissipation is consistent with the empirical heating rate curve shown above.
- Although we know that the WKB approximation breaks down in the corona, we integrated a "wave-action-like" conservation equation downwards (from 0.4 AU to the corona) as a first estimate of the relative amount of expected dissipation:

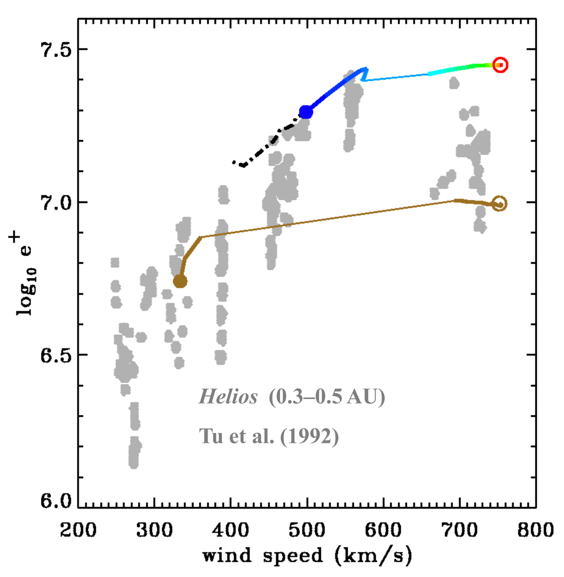


$$\frac{uV_A}{u+V_A}\frac{\partial}{\partial r}\left[\frac{(u+V_A)^2 Z_+^2}{uV_A}\right] = -\frac{4Q}{\rho}$$

- As expected from other studies, the wave power consistent with the empirical heating (**red curve**) is: (1) larger in amplitude, and (2) more consistent with the radial gradient in the *Helios* data points (**blue**), than one would expect from inward extrapolation without dissipation (black dotted curve).

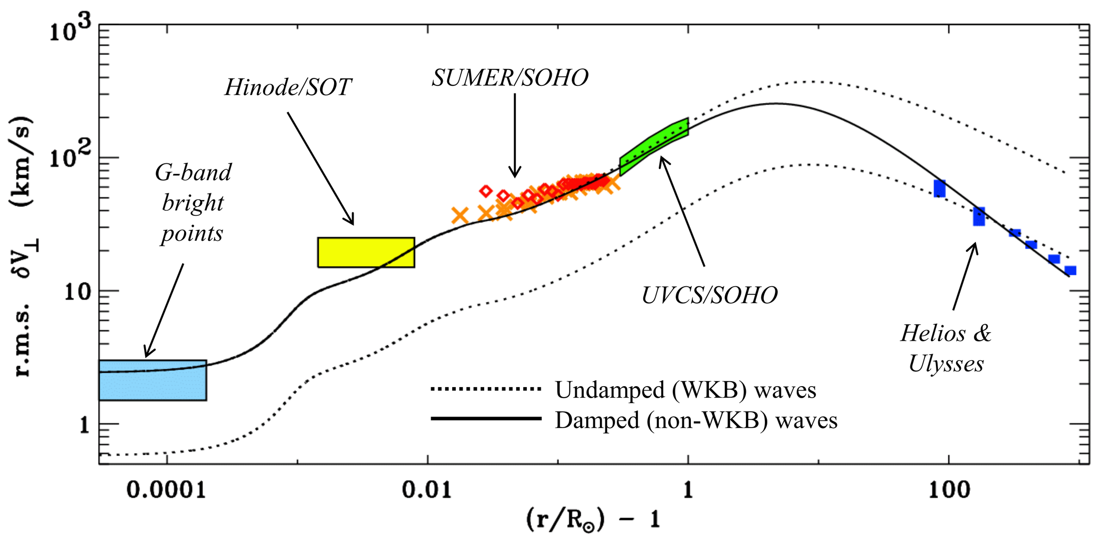
Do the in situ MHD fluctuations show higher wave amplitudes for faster wind streams?

- Possibly. Although Roberts et al. (1990) found no clear correlation between wind speed and ($\delta B/B_0$), Tu et al. (1992) did find a positive correlation between the wind speed and the **energy in outward-propagating fluctuations** at 0.3–0.5 AU.
- The wave/turbulence-driven models of Cranmer et al. (2007) showed a similar correlation as the Tu et al. (1992) results (**gray points**).
- Models that use a "standard" form for turbulent damping (Dobrowolny et al. 1980; Matthaeus & Zhou 1989; Oughton et al. 2006) are shown with **rainbow** colors (& **black** for wind from active regions).
- Models that use a more highly quenched form of turbulent dissipation in the limit of "rapidly escaping" Alfvén waves are shown in **brown**.



Are there Alfvén waves in the corona with amplitudes high enough to heat/accelerate the solar wind?

- Yes; there is a great deal of remote-sensing evidence in favor of Alfvénic fluctuations in the corona with amplitudes substantially higher than one would obtain from inward WKB extrapolation from *in situ* data.
- Summary of data from polar coronal holes (source regions of fast wind):



- Cranmer & van Ballegooijen (2005) described how horizontal motions of G-band intergranular bright points ($B \approx$ 1500 G) constrain the power spectrum of kink-mode oscillations of flux tubes in the photosphere (**cyan box**), and how these waves transform into volume-filling Alfvén waves as the height increases.

> Whether or not these flux tubes are **line-tied** from the standpoint of the corona does not affect the existence of these oscillations. The flux tubes move around on the surface with statistics somewhat resembling a zero-frequency "random walk" (see, e.g., van Ballegooijen 1986; van Ballegooijen et al. 1998), but with other (nonzero-frequency) components in their power spectrum as well.

- De Pontieu et al. (2007) observed swaying spicules in the vicinity of the Sun's transition region and put constraints on the Alfvén wave amplitude (**yellow box**).
- SUMER on *SOHO* separated thermal from "nonthermal" emission line widths for many ions, which constrains the transverse wave amplitude (**orange:** Banerjee et al. 1998; **red:** Landi & Cranmer 2009). UVCS on *SOHO* was used in the same way at larger heights (**green:** Esser et al. 1999).
- Extrapolating inward from the *in situ* data (shown here in **blue** from Bavassano et al. 2000) assuming undamped (WKB, outward-propagating) Alfven waves gives insufficient power in the corona to account for the remote-sensing observations.
- Extrapolating outward from the remote-sensing data with undamped WKB waves gives too much power in the heliosphere to account for the *in situ* data.
- The solid curve above shows the result of a damped (non-WKB) model of outward and inward Alfven waves, where the dissipation was computed according to phenomenological models of MHD turbulence (Cranmer & van Ballegooijen 2005). **The same amount of turbulent damping generated the "right" amount of coronal heating to account for high-speed solar wind acceleration.**

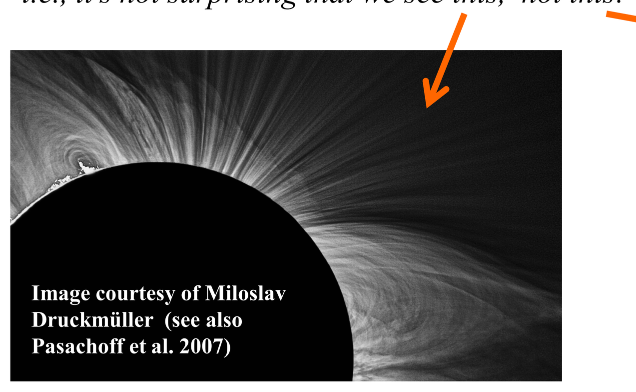
Are the coronal Alfvén waves turbulent?

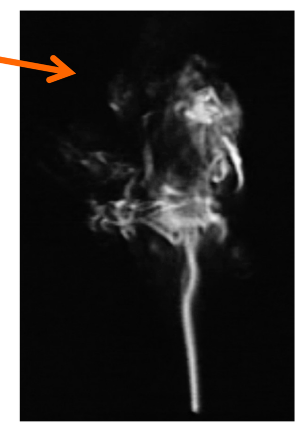
- There is indirect evidence that they are:
- Radio observations show a broad, power-law-like spectrum of **density fluctuations** extending to small scales at heliocentric radii as small as 5 R_s, as would be expected from turbulent mixing of passive-scalar density fluctuations (e.g., Spangler 1996, 2002; Harmon & Coles 2005; Chandran et al. 2009).
- The *Helios* probes measured **Faraday rotation fluctuations** (FRFs) of polarized radio signals that passed through the corona at impact parameters between 2 and 15 R_s in the ecliptic plane. The magnitude of these fluctuations depends not only on wave amplitudes, but also quite sensitively on the **turbulent correlation length.** Hollweg et al. (2010) recently compared measured FRFs with predicted values from the wave/turbulence model of Cranmer et al. (2007), and found excellent agreement for the equatorial streamer model corresponding to a flux tube originating at a colatitude of 28°.

Are eclipse/coronagraph images consistent with the presence of Alfvén waves of the magnitude required to heat the corona?

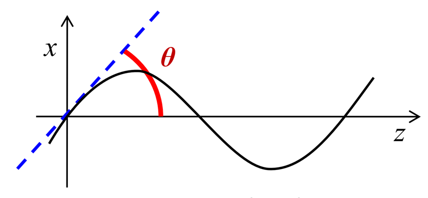
- Yes. The predicted "wiggles" in the field lines should not be exaggerated enough to see in "snapshot" images in the corona.

i.e., it's not surprising that we see this, not this:

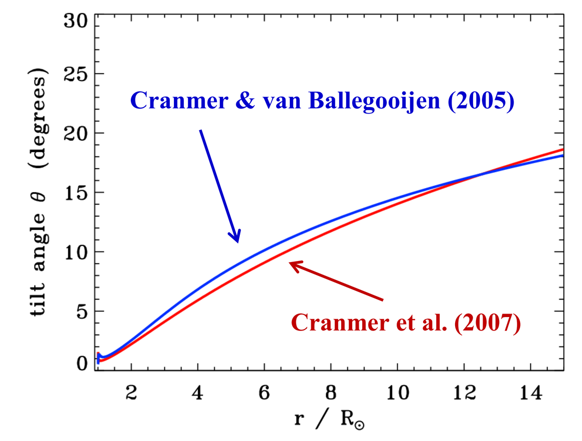




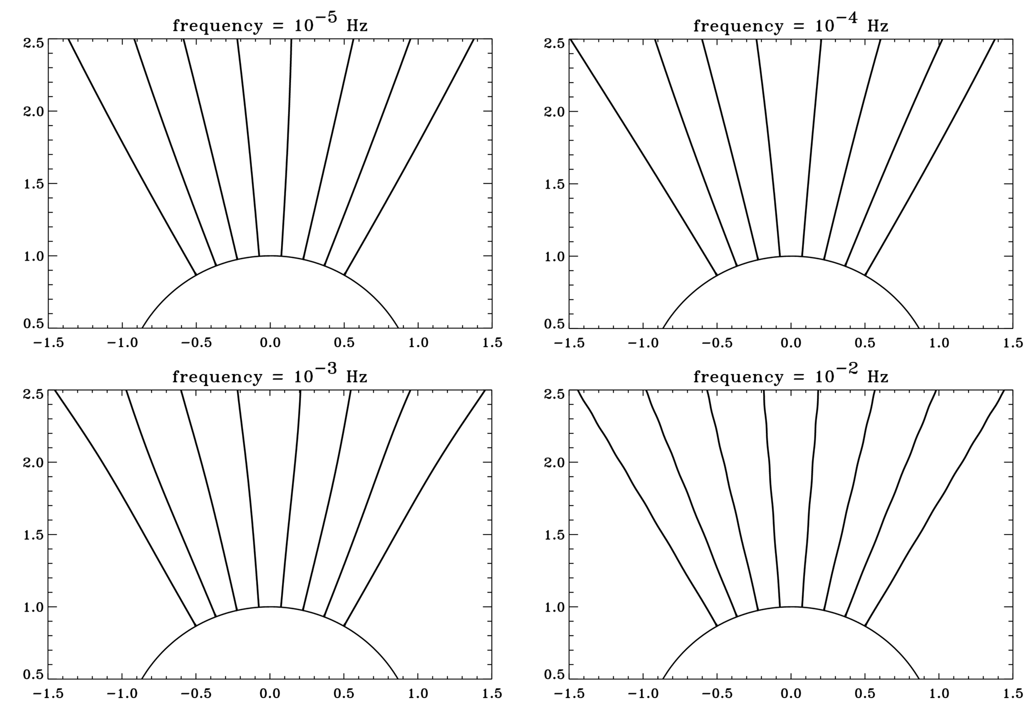
- For monochromatic Alfvén waves (linearly polarized in the "plane of the sky"), the **maximum angular deviation** from the background field direction can be computed from models that contain enough wave energy to heat the corona and accelerate the wind. Near the Sun, these angles are **small:**



$$\theta = \tan^{-1}\left(\frac{dx}{dz}\right) = \tan^{-1}\left(\frac{\delta B_x}{B_{z0}}\right)$$



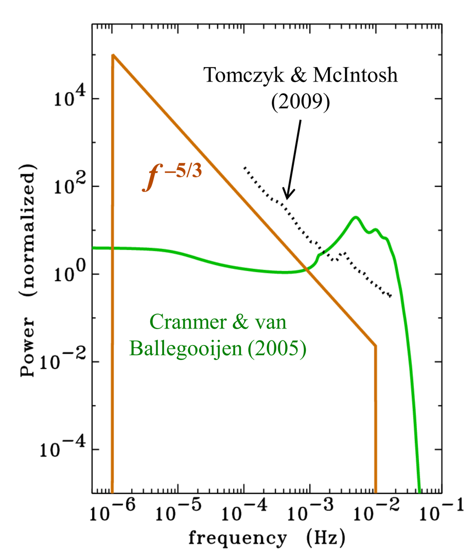
- For these same monochromatic Alfvén waves, we can simulate the **field-line displacements**, assuming that in each case *all* of the wave power is at a given monochromatic frequency (8 random phases shown for each frequency):



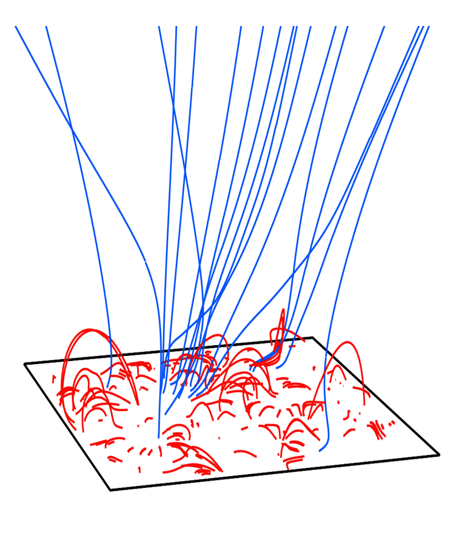
- Overall, the "wiggles" appear small enough to be consistent with eclipse and coronagraph images like the one shown above.
- Note, however, that the above models must be **overestimating** the wiggles:
  - In reality, there is a broad power spectrum, with each "frequency bin" exhibiting smaller displacements, randomly phased from the other bins.
  - In reality, there are dozens (hundreds?) of flux tubes along a given observational line of sight, and the white-light eclipse/coronagraph images show the *integral* along that line of sight. The observed striations must suffer from $\sqrt{N}$ cancellation/smearing effects.
- It may be possible to use high-quality, high-cadence **SDO/AIA** image sequences to probe the small predicted displacements, but earlier data have been inadequate.

Do we understand how the frequency spectrum of MHD fluctuations evolves from photosphere to corona to heliosphere?

- No! But we do have some interesting constraints . . .
- Dominant periods around **3–10 minutes** are apparent in photospheric measurements (i.e., G-band bright points; see Cranmer & van Ballegooijen 2005), *Hinode*/SOT spicule measurements (De Pontieu et al. 2007), and ground-based Doppler images of off-limb active regions (Tomczyk & McIntosh 2009).
- *In situ* data show power extending to much longer periods (**hours → days**), as emphasized by Roberts (2010).
- How does the Sun bridge this gap?
- It has been suggested (e.g., Borovsky 2008) that some of the *in situ* fluctuations are due to spacecraft flying through uncorrelated flux tubes; the spatial scales of these flux tubes may correspond to the frequency at which the *in situ* power spectrum changes from f^{-1} to $f^{-5/3}$.



- Can this idea be tested by spacecraft that co-rotate with the Sun, such as *Solar Orbiter?*
- Alternatively, the complex evolution of flux tubes in the Sun's **magnetic carpet** may generate Alfvén waves with periods of order the "recycling timescale" of the field (i.e., **~1–2 hours**) (see, e.g., Hollweg 1990; Cranmer & van Ballegooijen 2010).
- The statistical properties of these fluctuations may be consistent with the diffusive motions of coronal field-line footpoints (Matthaeus & Goldstein 1986; Giacalone & Jokipii 2004; Nicol et al. 2009).



Do we understand the micro-scale mechanisms by which MHD turbulence is dissipated?

- No, but there have been a number of suggested ways that low-frequency "Quasi-2D" turbulence could naturally give rise to kinetic-scale **preferential ion energization** (as is observed; see Kohl et al. 2006; Marsch 2006; Cranmer 2002, 2009)**:**
  - When MHD turbulence cascades to small perpendicular scales, small-scale **shearing motions** may be able to generate ion cyclotron waves (Markovskii et al. 2006).
  - Dissipation-scale **current sheets** may preferentially "spin up" ions perpendicularly to the large-scale magnetic field (Dmitruk et al. 2004).
  - If MHD turbulence exists for both Alfvén and fast-mode waves, the two types of waves can **nonlinearly couple** with one another to produce ion cyclotron waves (Chandran 2005).
  - If **nanoflare-like reconnection events** in the low corona are frequent enough, they may fill the extended corona with electron beams that would become unstable and produce ion cyclotron waves (Markovskii 2007).
  - If **kinetic Alfvén waves** reach large enough amplitudes, they can damp via stochastic wave-particle interactions and heat ions (Voitenko & Goossens 2004; Chandran 2010).
- Despite ongoing controversies about the physics of imbalanced MHD turbulence (*see the SHINE session on this topic!*), there exists much evidence that phenomenological scaling relations (i.e., von-Kármán-like "outer scale" cascade/dissipation rates) do a reasonably good job of reproducing the overall rate of dissipation from numerical simulations (e.g., Hossain et al. 1995; Dmitruk et al. 2001; Wan et al. 2010).

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