The Turbulent Cascade and Proton Heating of the Solar Wind during Solar Minimum

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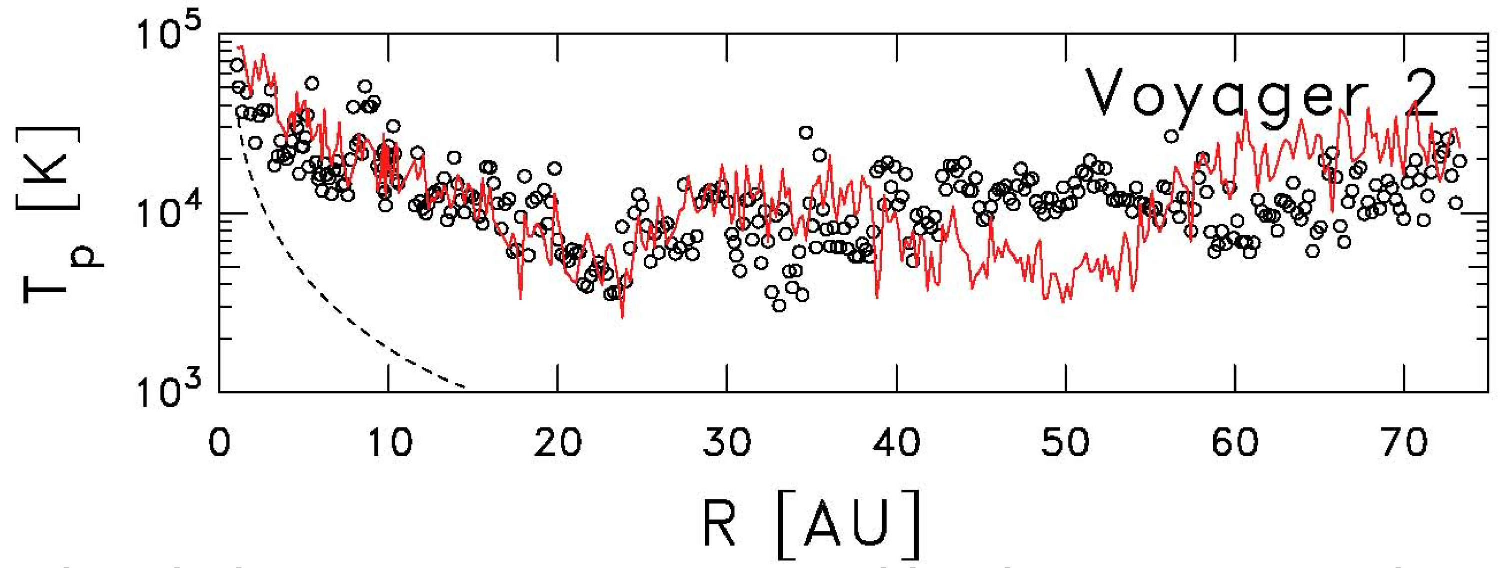
Abstract

The modern interpretation of solar wind dynamics draws from the traditional theory of hydrodynamic turbulence. Third moment theory was developed by Kolmogorov [1941a,b] and has been extended to magnetohydrodynamics by Politano & Pouquet [1998a,b]. We apply third-moment laws to observations of the solar wind at 1 AU and compare the rate of energy cascade during two significantly different phases of solar activity: solar maximum(1998-05) and solar minimum(2007-09). Traditional views are that when the activity is low, the source of the solar wind is thought to be quiet and the heating due to turbulence would follow this trend. We find that the turbulent cascade is virtually identical to solar maximum conditions.

Solar Wind Turbulence

Measurements of the solar wind display a non-adiabatic cooling rate that suggests an in situ heating process beyond compression regions and shocks. Predictions of MHD turbulence energy cascade rates provide a great measure of the heating rate.



The circles are measurements taking by Voyager 2, the dotted line is the predicted adiabatic cooling curve and red is the prediction from turbulent transport theory. Note the drastic separation and continual heating the solar wind experiences as it propagates away from the sun.

Third Moments and Energy Cascade

Epsilon is the predicted rate of energy cascade in the inertial range of a turbulent system. It has been shown that it is related to the third moment of the velocity fluctuations.

The hydrodynamic third moment:

$$S_{3,Hyd} = \left\langle [\Delta V(x+L)]^3 \right\rangle = -\frac{4}{5}\epsilon_{hyd} L$$

The MHD isotropic analog has been derived:

$$D^{\pm}_{3,iso} = \left\langle [\Delta Z^{\mp}_R(x+L)] \sum_i [\Delta Z^{\pm}_i(x+L)]^2 \right\rangle = -\frac{4}{3}\epsilon^{\pm}_{iso} L$$

Where the velocity is the in Alfven units:

$$Z^{\pm}_i(x) = V_i(x) \pm \frac{B_i(x)}{\sqrt{4\pi\rho}}$$

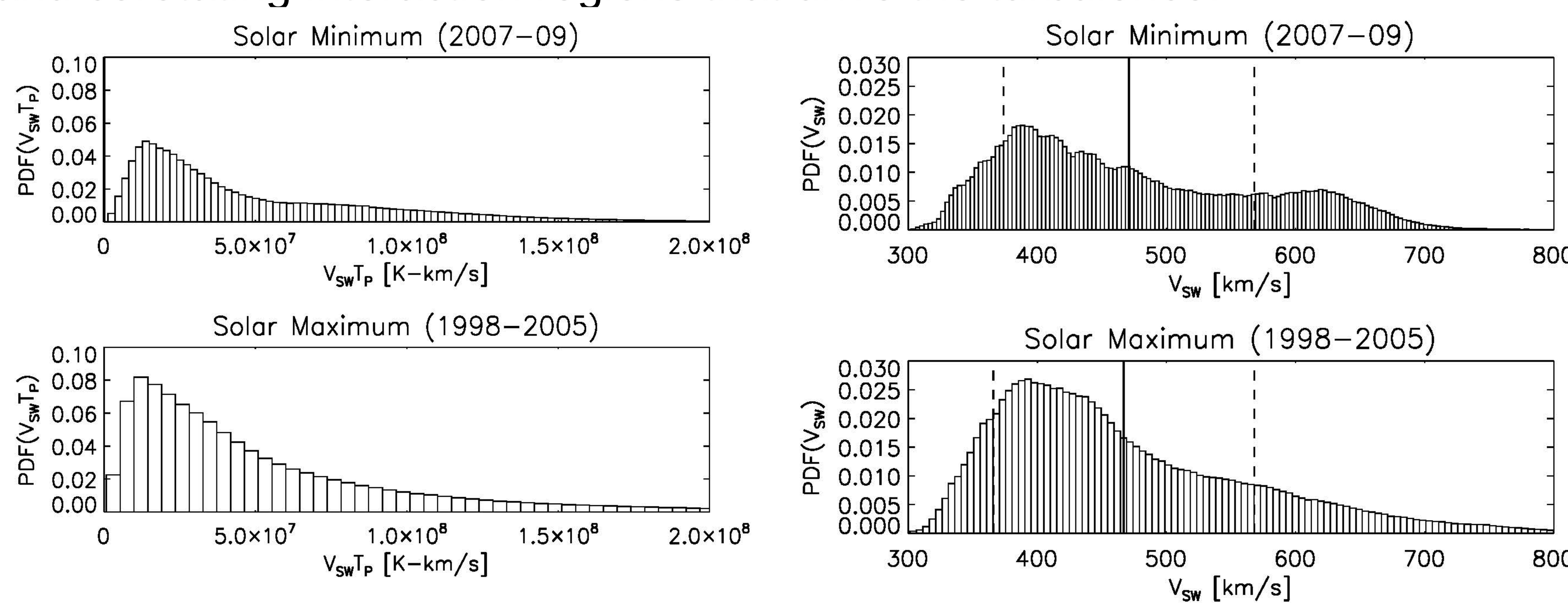
The hybrid formalism MacBride[2008]:

$$D^{\pm}_{3,\perp} = \left\langle [\Delta Z^{\mp}_{\perp}(x+L)] \sum_i [\Delta Z^{\pm}_i(x+L)]^2 \right\rangle = -2\epsilon^{\pm}_{\perp} L\, cos(\theta_{BR})$$

$$D^{\pm}_{3,\parallel} = \left\langle [\Delta Z^{\mp}_{\parallel}(x+L)] \sum_i [\Delta Z^{\pm}_i(x+L)]^2 \right\rangle = -4\epsilon^{\pm}_{\parallel} L\, sin(\theta_{BR})$$

Observations of the Solar Cycle

Solar minimum (2007-09) solar wind is characterized by a more steady flow with localized fast winds at the poles. Solar maximum (1998-2005) is dominated by chaotic flows and transients such as coronal mass ejections and corotating interaction regions that drive the turbulence.



Velocity-temperature distributions change insignificantly over phase of solar cycle. Solar minimum coronal hole locations explain wind speed disagreement

Proton Heating and Energy Cascade

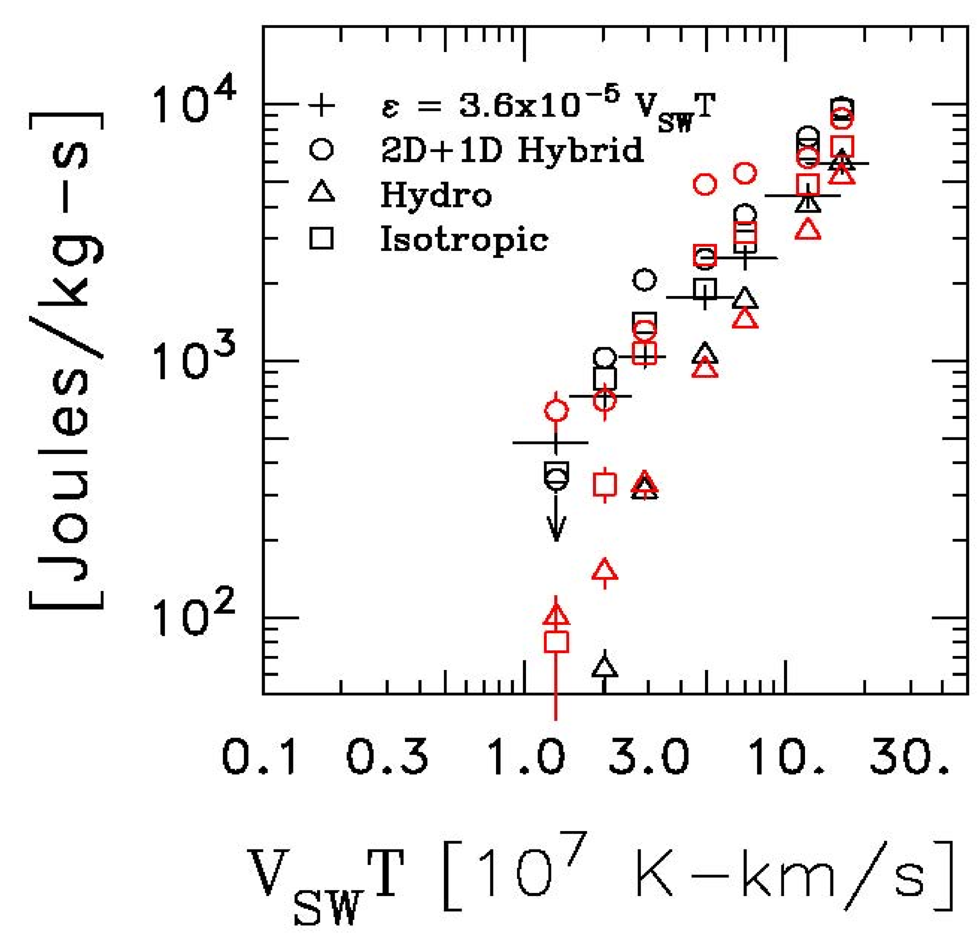
The energy cascade rates we calculate with third moment theory are backed by an empirical heating rate Vasquez et. al.

$$\epsilon_{heat} = 3.6 \times 10^{-5}\, T_p V_{SW} (J\, kg^{-1}\, s^{-1})$$

The heating rate is proportional to the product of the velocity and temperature. In our analysis we bin the data set and compute an energy cascade rate. This is a validation of our analysis, published in Stawarz[2009]. Further considerations of the ability of the third moment techniques to characterize the heating rate of the solar wind lead us to analyze the two phases of the solar cycle.

Red is computed during solar minimum and **black** during maximum. The expected heating rates did not differ significantly between phases of the solar cycle.

- The heating rate matches the energy cascade rate
- Isotropic formalism seems to be a better estimate than hybrid
- Solar Min. underestimate at lower VT bins
- This analysis does not include heating due to electrons

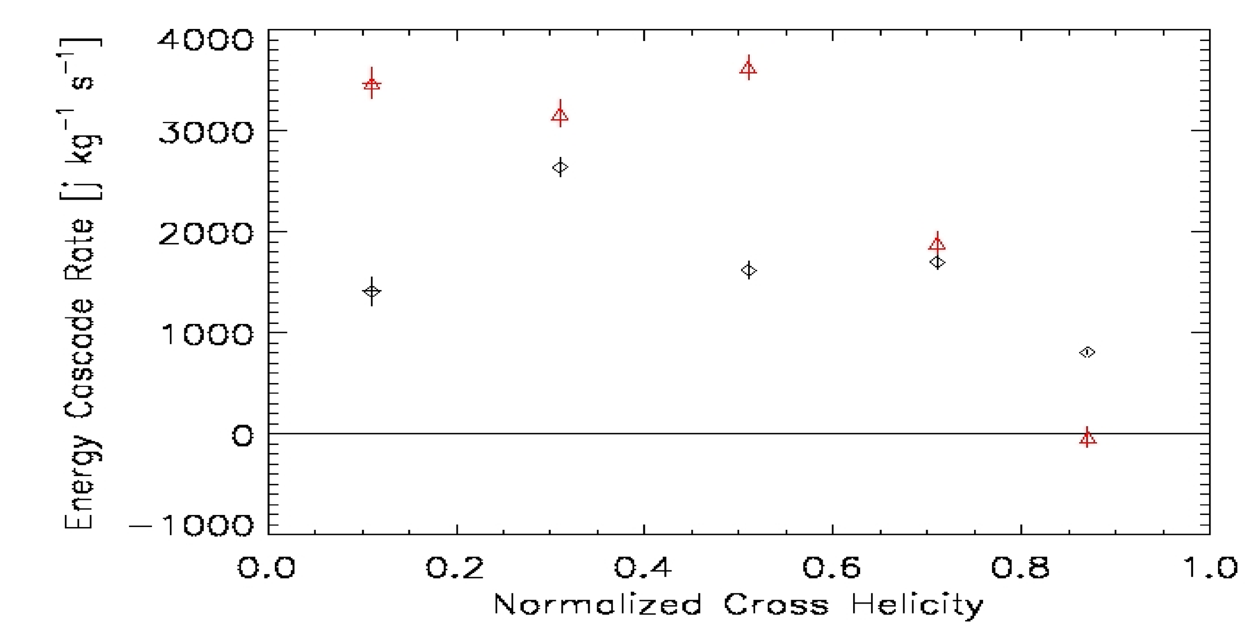


Cross Helicity

The turbulent nature of any fluid is generated by non-linear interactions, for a plasma this is the interactions between Z+ and Z-. Cross helicity is a measure of the correlation between the magnetic field and plasma velocity

$$H_c \equiv [\delta V \cdot \delta B] = \frac{1}{4}[(\delta Z^+)^2 - (\delta Z^-)^2]$$

Normalized by the energy we recover a unit less quantity that describes the state of the solar wind. The level of turbulence is related to the cross helicity.



Red is outward (+) component and **black** is the inward (-) component.

Conclusion

- The non-adiabatic evolution of the solar wind is well described by MHD turbulence.
- The third moment prediction of the turbulent energy cascade rate of the solar wind matches the expected heating rate.
- This analysis is not limited to active phases of the solar cycle, which suggests the wind generates turbulence.
- The level of turbulence is related to the cross helicity.
- Future work: Explain negative energy cascade rates.

References

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