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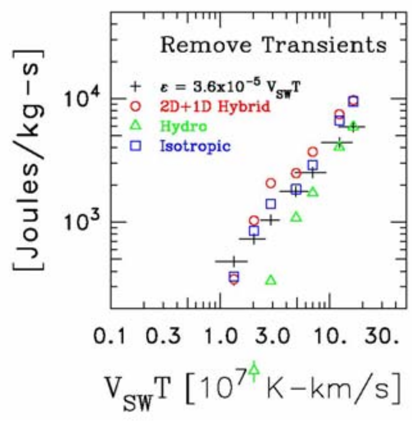
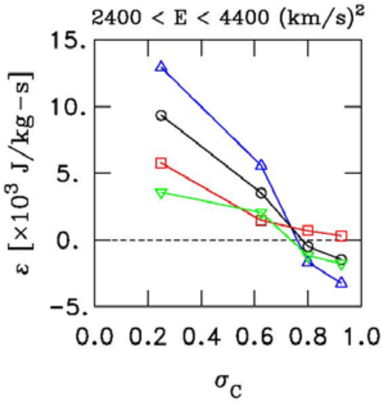
Direct Measurement of the Turbulent Cascade in Interplanetary Space

In ACE News #108 we described preliminary results from a study that uses third moment methods from hydrodynamic and magnetohydrodynamic (MHD) turbulence theory to measure the in-situ heating rate in the local solar wind due to the dissipation of the observed turbulence. The method is based on the idea of an inertial cascade of turbulence from large to small scales developed by Kolmogorov (1941) for hydrodynamics. Here we report on our (Stawarz et al., 2009) comparison of the computed heating rate with the apparent heating rate inferred from the non-adiabatic radial gradient of proton temperature (Vasquez et al., 2007), as a function of the local value of VT, (solar wind speed × temperature), and on our (Smith, et al., 2009, Stawarz et al 2010, in press) computed heating rates as a function of the turbulent energy and bulk cross-helicity in the solar wind.

Kolmogorov (1941) showed from the Navier-Stokes (fluid) equations that in isotropic hydrodynamics the third moment of parallel fluctuations obeys the relations $S_3(\mathbf{L}) \equiv \langle [V_{||}(\mathbf{x}) - V_{||}(\mathbf{x}+\mathbf{L})]^3 \rangle = \langle [\delta V_{||}(\mathbf{L})]^3 \rangle = -(4/5)\varepsilon|\mathbf{L}|$. $V_{||}(\mathbf{x})$ is the component of the wind velocity at point **x** measured along the separation vector **L** and ε is the dissipation rate of turbulent energy per unit mass. The isotropic form of the MHD expression (Politano and Pouquet, 1998b) is $D_3 \pm(\mathbf{L}) = \langle \delta Z_{||}^{\pm}(\mathbf{L}) |\delta \mathbf{Z}^{\pm}(\mathbf{L})|^2 \rangle = -(4/3)\varepsilon|\mathbf{L}|$ where $\mathbf{Z}^{\pm}(\mathbf{x}) \equiv \mathbf{V}(\mathbf{x}) \pm \mathbf{B}(\mathbf{x})/\sqrt{(4\pi\rho)}$ are the Elsasser fields and $Z_{||}$ is the component parallel to the separation vector **L**. We check that the third moment is indeed linear in L, and use these expressions, which assume homogeneity and incompressibility and that **L** is in the inertial range, to calculate ε. We have applied these expressions to 10 years of ACE observations and from the slope of the computed third moments we extract estimates of the solar wind heating rate.





The figure (top) shows our VT study results (Stawarz, et al. 2009). We divided the ACE data into 7 bins according to the product $V_{SW}T_P$, computed heating rate ε from the third moment scaling and compared with the Vasquez et al. (2007) value $\varepsilon_P = 3.6 \times 10^{-5}\, V_{SW}T_P$. While the hydrodynamic expression consistently underestimates proton heating, both the isotropic and hybrid geometries of the MHD forms predict *slightly* more energy dissipation than is needed to heat the thermal protons. Preliminary studies suggest that this excess in the energy cascade is consistent with the amount of energy required to heat the background electrons either by plasma processes such as Landau resonance or via a secondary cascade that extends to electron cyclotron scales (Saito et al., 2008).

The figure (bottom) shows the results of the cross-helicity study (Smith et al. 2009, Starwarz, et al. 2010). Cascade rates for: Sunward-propagating waves (red); anti-Sunward propagating waves (blue); the total energy [(red+blue)/2] (black); and the cross-helicity [(blue-red)/2] in green, are plotted against the bulk normalized cross-field correlation $\sigma_C \equiv 2\langle \delta\mathbf{V} \bullet \delta\mathbf{B} \rangle / \langle (\delta\mathbf{B})^2 + (\delta\mathbf{V})^2 \rangle$. Intervals with $|\sigma_C| \rightarrow 1$ have mostly outward propagating waves. This analysis shows that the energy dissipation rate is not just proportional to the total energy in turbulence, but for a given turbulent energy range, decreases as $|\sigma_C|$ increases. At high $|\sigma_C|$, ε (outward) becomes *negative*. This means that the dominant anti-Sunward component is reinforced when it is very dominant, rather than dissipated, (Smith et al. 2009; Stawarz et al. 2010).

This and related studies continue to address the long-standing question "Are solar wind fluctuations merely remnant features of the acceleration process such as waves that propagate largely undisturbed over large regions of interplanetary space, or do they arise *in situ* via processes such as stream interaction to form an MHD analog to inertial-range hydrodynamic turbulence?" Increasingly, the answer is the latter.

Contributed by Joshua Stawarz, Charles Smith, Bernard Vasquez, Miriam Forman, and Benjamin MacBride of the ACE Science Team. Address comments and questions to Charles.Smith@unh.edu. See http://www.srl.caltech.edu/ACE/ACENews_Archives.html for an archive of earlier ACE News items.