

The Effect of Magnetic Turbulence Energy Spectral Scaling on the Heating of the Solar Wind

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MHD turbulence

Energy cascade possible only if two Alfvén wave packets propagating in opposite directions collide

Dimensionless parameter: $\chi \equiv k^{1/2} E_k^{1/2} V_A^{-1} = v_k / V_A \ll 1$

- Time scales:

- ◆ Eddy turn-over time $\tau_N \sim 1 / kv_k$

- ◆ Alfvén time $\tau_A \sim 1 / kV_A = \chi \tau_N \ll \tau_N$

- ◆ Energy cascade time $\tau_E \sim \tau_A / \chi^2 = \tau_N / \chi \gg \tau_N$

Kolmogorov cascade rate: $\varepsilon_K \sim v_k^2 / \tau_N \sim k^{5/2} E_k^{3/2}$

IK cascade rate: $\varepsilon_{IK} \sim v_k^2 / \tau_E \sim \varepsilon_K \chi \sim k^3 E_k^2 V_A^{-1} \ll \varepsilon_K$

Iroshnikov (1963), Kraichnan (1965)

Solar wind turbulence model

The steady state solar wind turbulence model developed by [Matthaeus et al. 1994, 1996] and later developments:

Assumptions:

- ◆ Steady state
- ◆ Radially expanding solar wind with uniform speed V_{sw}
- ◆ 1D (radial position r)
- ◆ Turbulence characterized by two fields: fluctuation velocity (Z) and correlation length (λ)
- ◆ Kolmogorov type cascade rate
- ◆ Solar wind (proton) temperature can be calculated passively

Solar wind turbulence model

The steady state solar wind turbulence model developed by [Matthaeus et al. 1994, 1996] and later developments:

$$\frac{dZ^2}{dr} = -\frac{AZ^2}{r} - \frac{\alpha Z^3}{\lambda V_{SW}} + \frac{Q}{V_{SW}}$$

$$\frac{d\lambda}{dr} = -\frac{C\lambda}{r} + \frac{\beta Z}{V_{SW}} - \frac{\beta\lambda Q}{V_{SW}Z^2}$$

$$\frac{dT}{dr} = -\frac{4T}{3r} + \frac{m\alpha Z^3}{3k_B\lambda V_{SW}}$$

Z^2 : average turbulence energy with $Z_+^2 = Z_-^2$

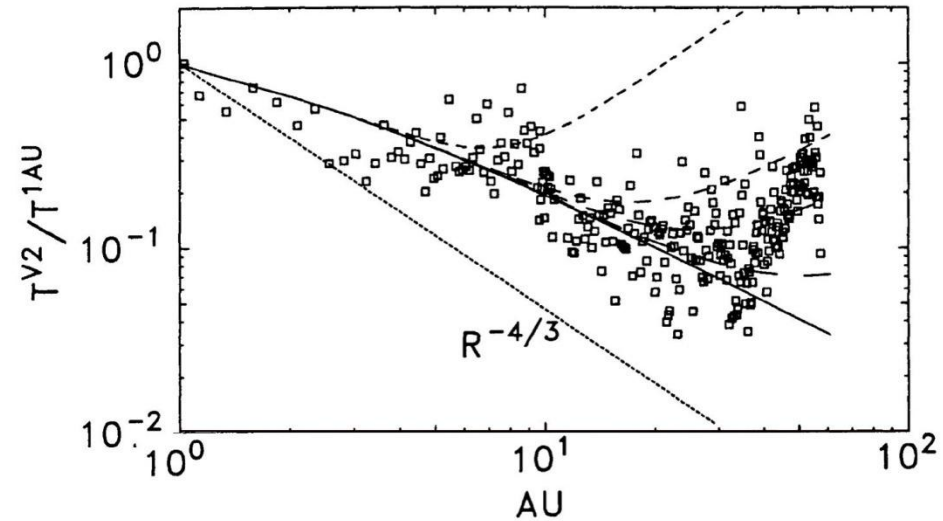
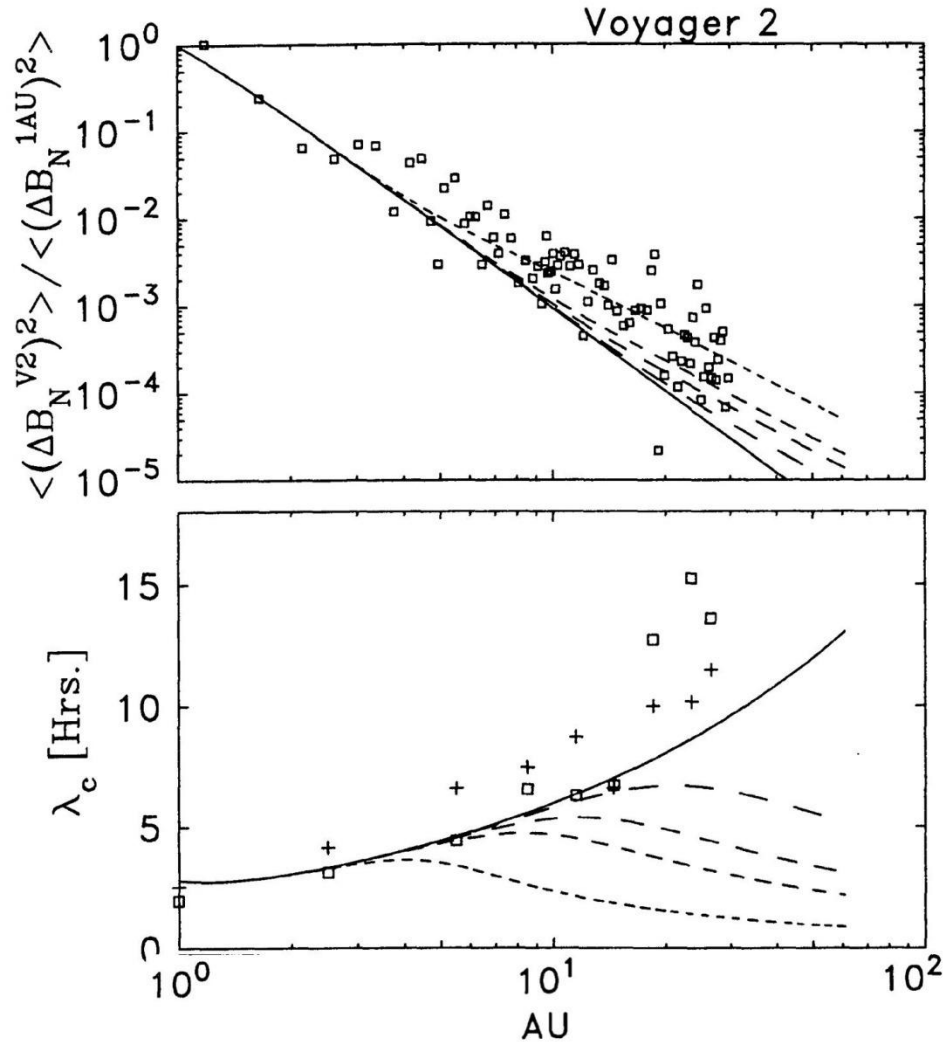
λ : turbulence correlation length

T : solar wind proton temperature

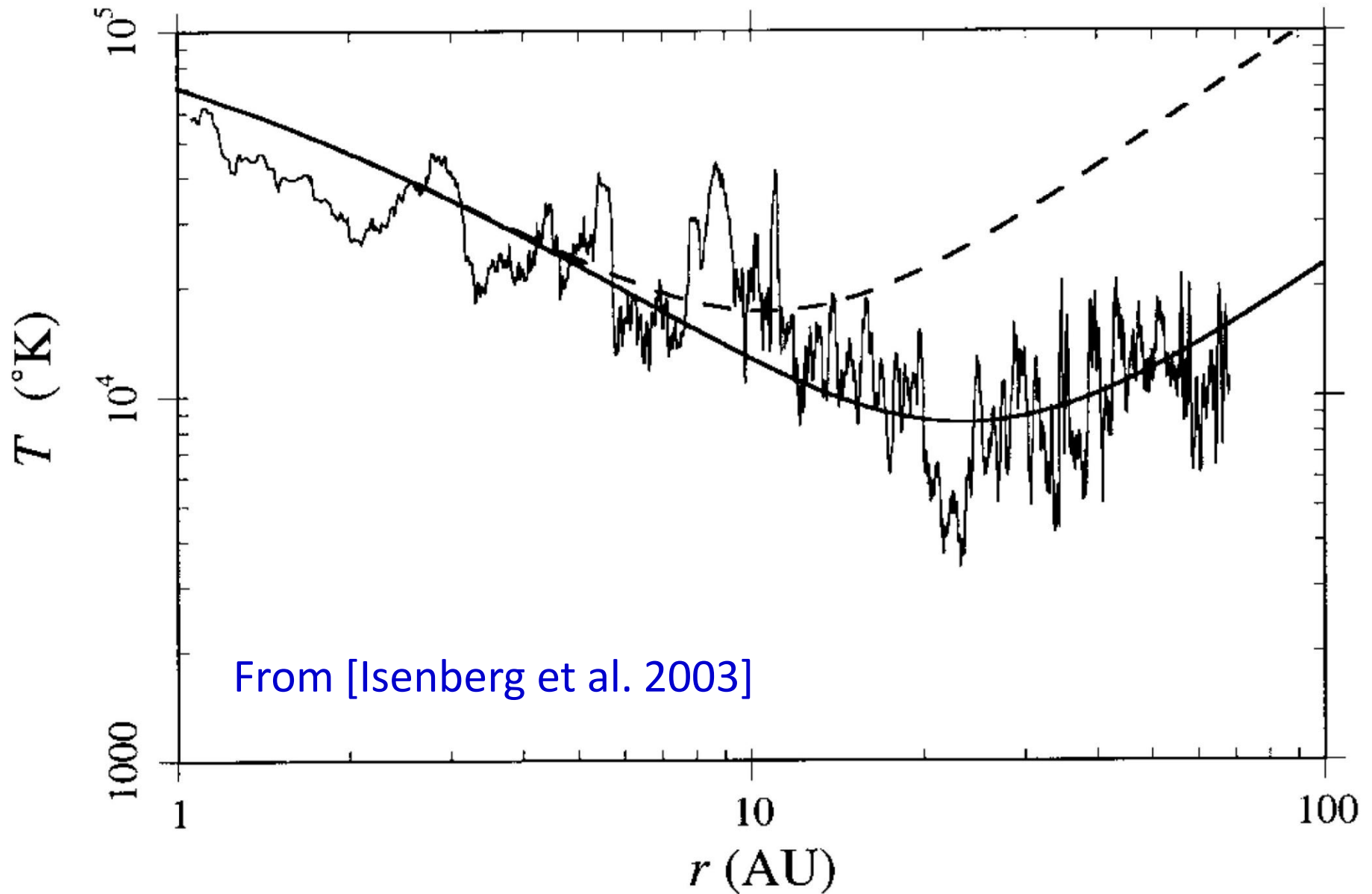
Q : turbulence generation rate due to pickup ions (interstellar neutral particles entering the heliosphere and get ionized)

Solar wind turbulence model vs observations

From [Smith et al. 2001]



Temperature comparison with pickup ions



Solar wind model with IK cascade

The solar wind turbulence model changed to [Matthaeus et al. 1994, Hossain et al. 1995]:

$$\frac{dZ^2}{dr} = -\frac{AZ^2}{r} - \frac{\alpha Z^4}{\lambda V_{SW} V_A} + \frac{Q}{V_{SW}}$$
$$\frac{d\lambda}{dr} = -\frac{C\lambda}{r} + \frac{\beta}{V_{SW}} \left(\frac{Z^4}{V_A} \right)^{1/3} - \frac{\beta\lambda Q}{V_{SW} Z^2}$$
$$\frac{dT}{dr} = -\frac{4T}{3r} + \frac{m\alpha Z^4}{3k_B \lambda V_{SW} V_A}$$

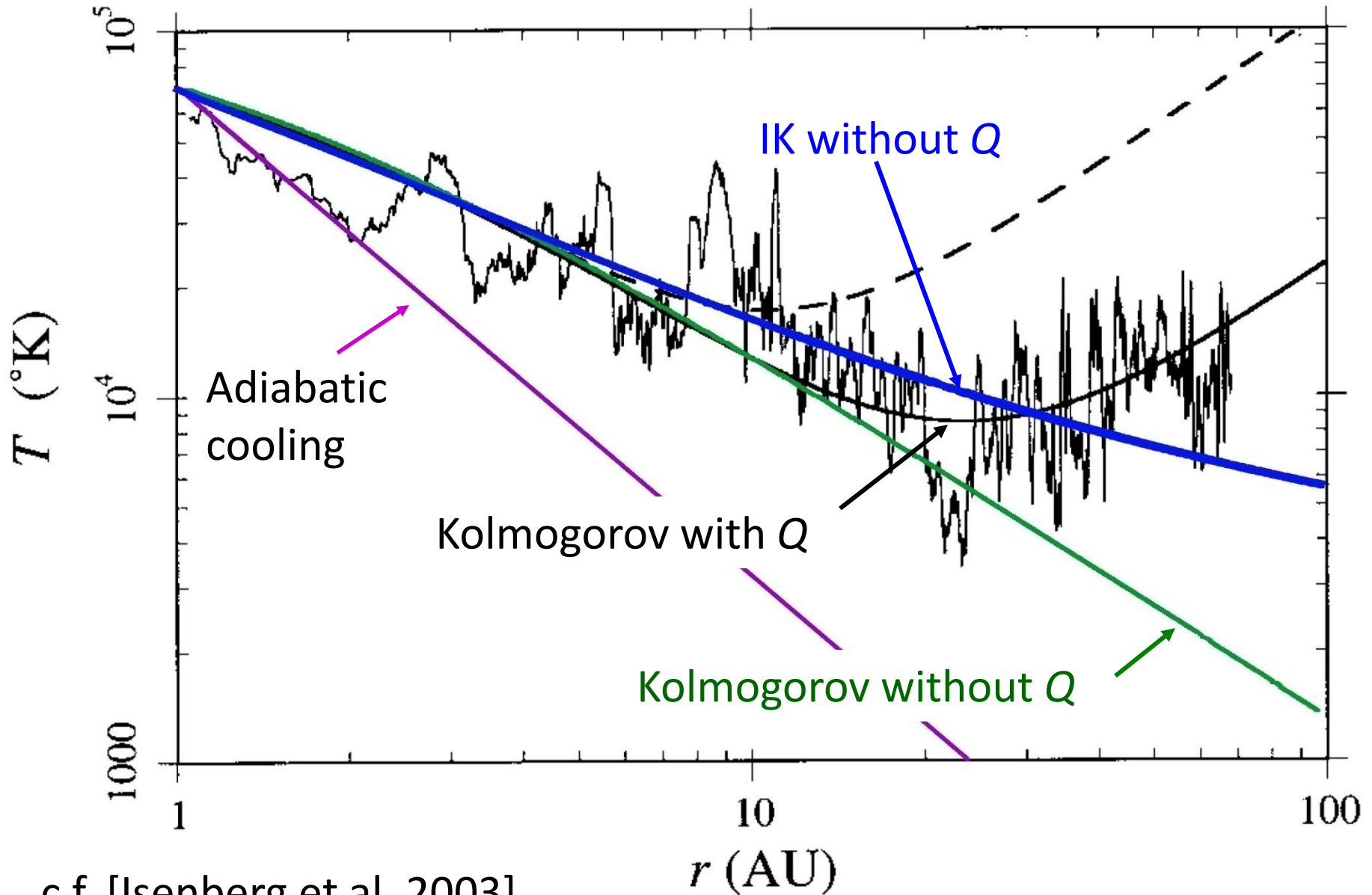
Z^2 : average turbulence energy with $Z_+^2 = Z_-^2$

λ : turbulence correlation length

T : solar wind temperature

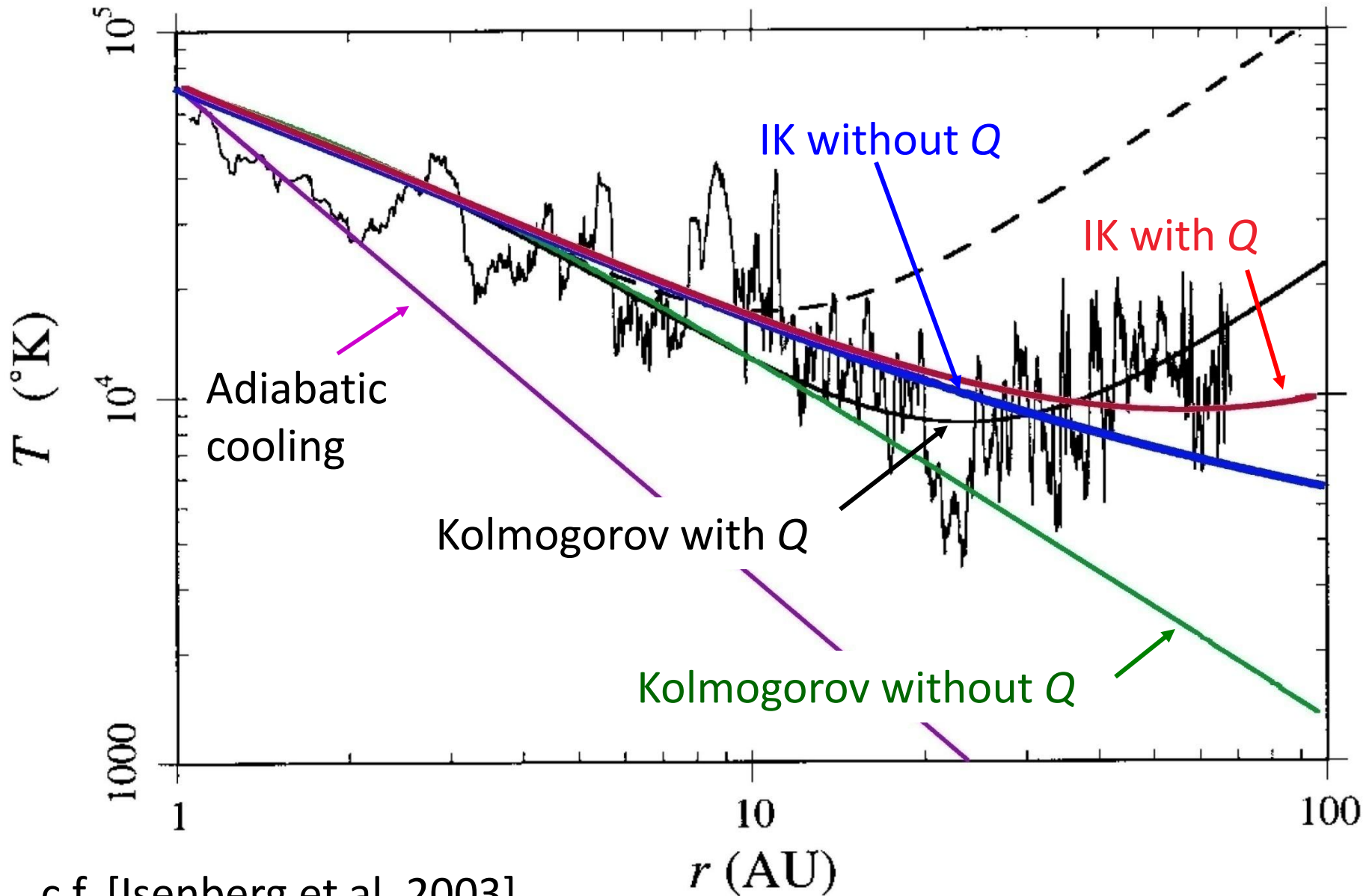
Q : turbulence generation rate due to pickup ions (also depends on the turbulence energy spectrum)

Comparisons with observations



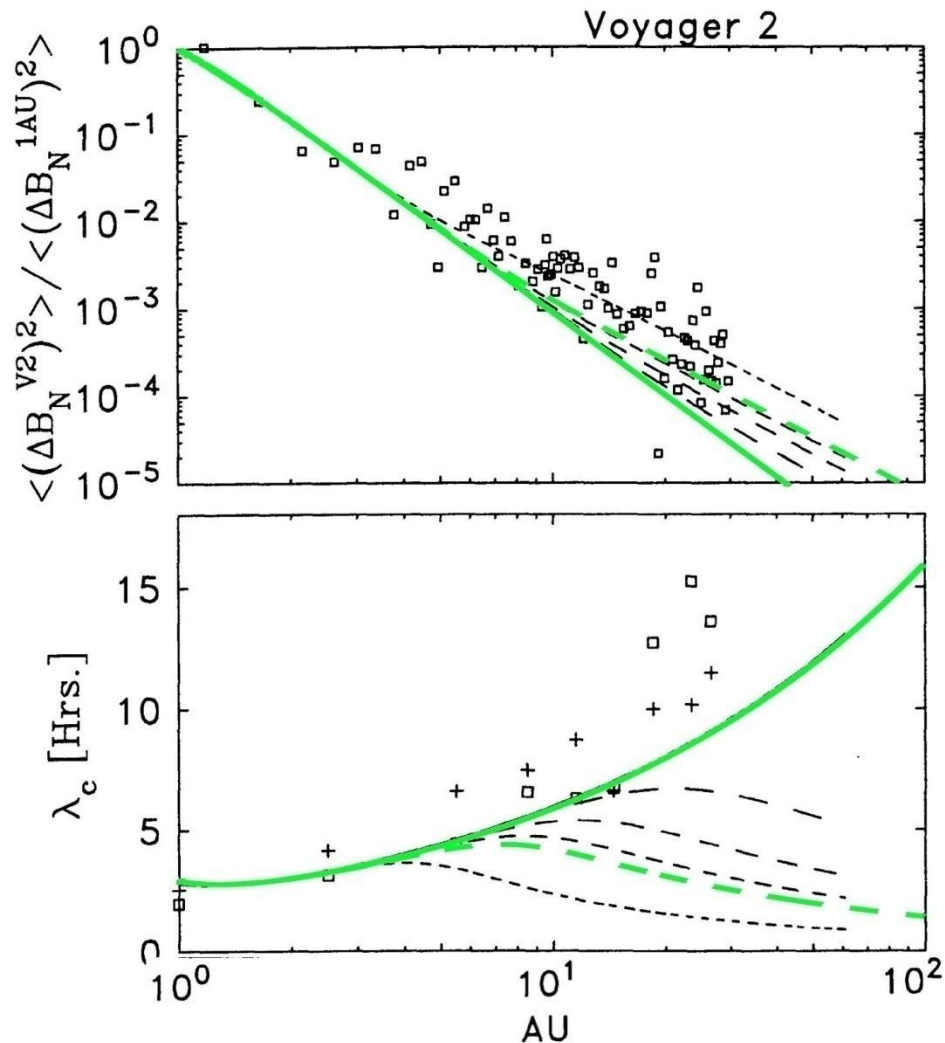
c.f. [Isenberg et al. 2003]

Comparisons with observations

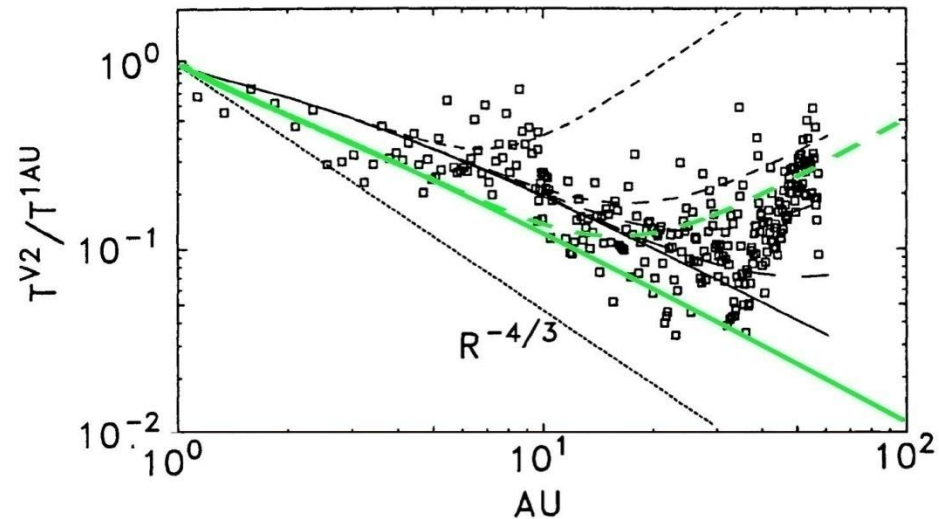


c.f. [Isenberg et al. 2003]

Comparisons with observations

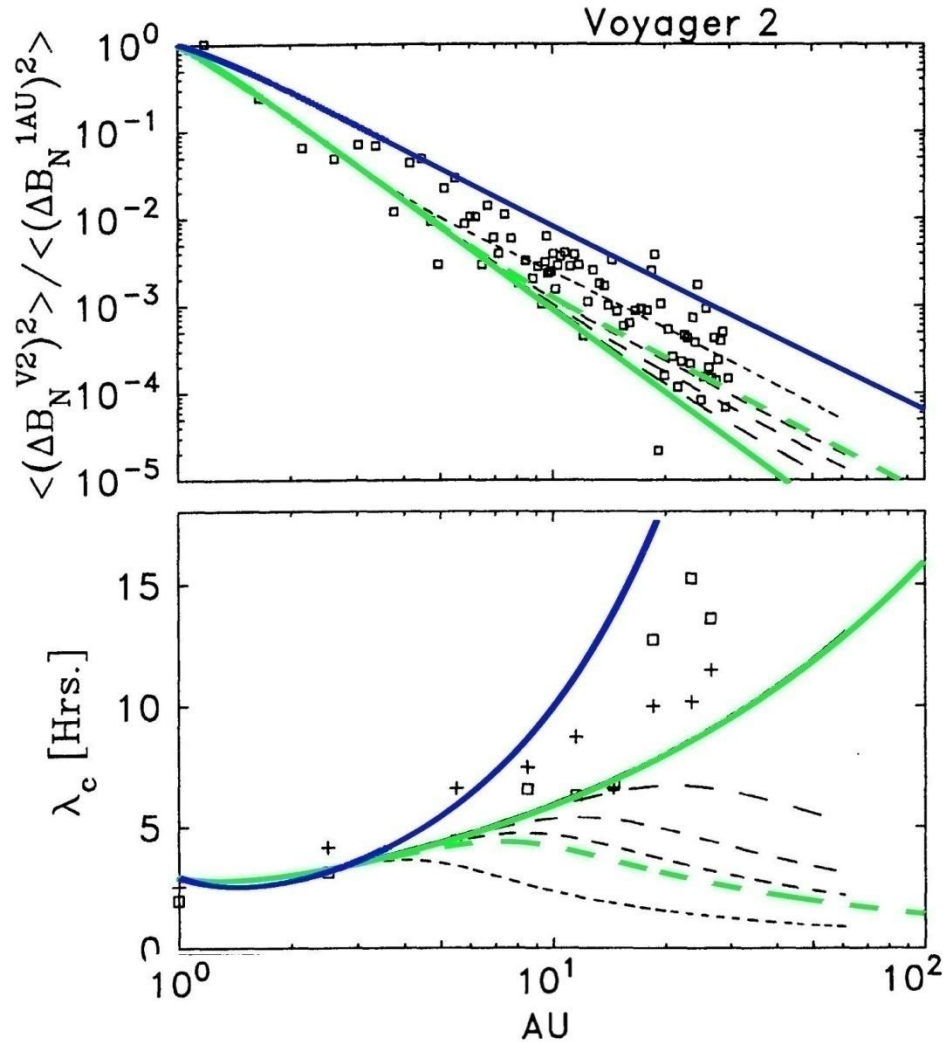


- Kolmogorov without Q
- - - Kolmogorov with Q

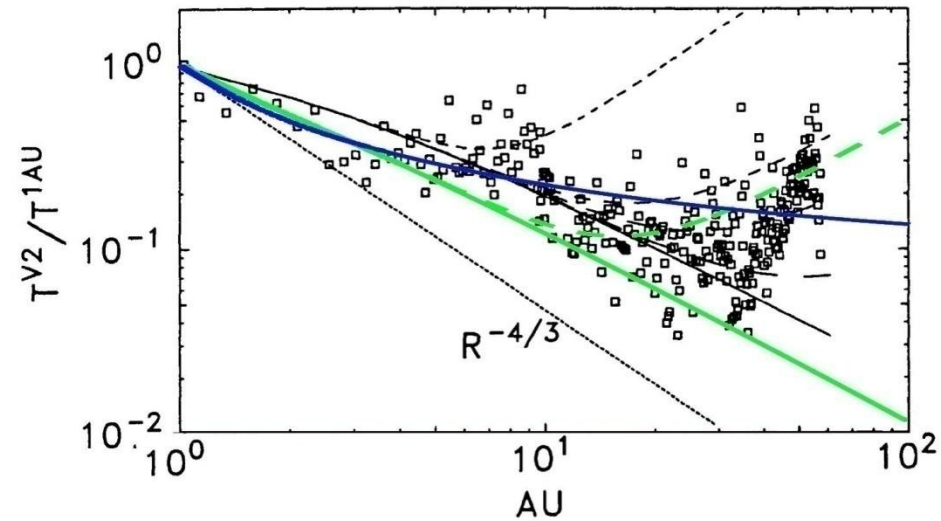


C.f. [Smith et al. 2001], with corrected temperature equation.

Comparisons with observations

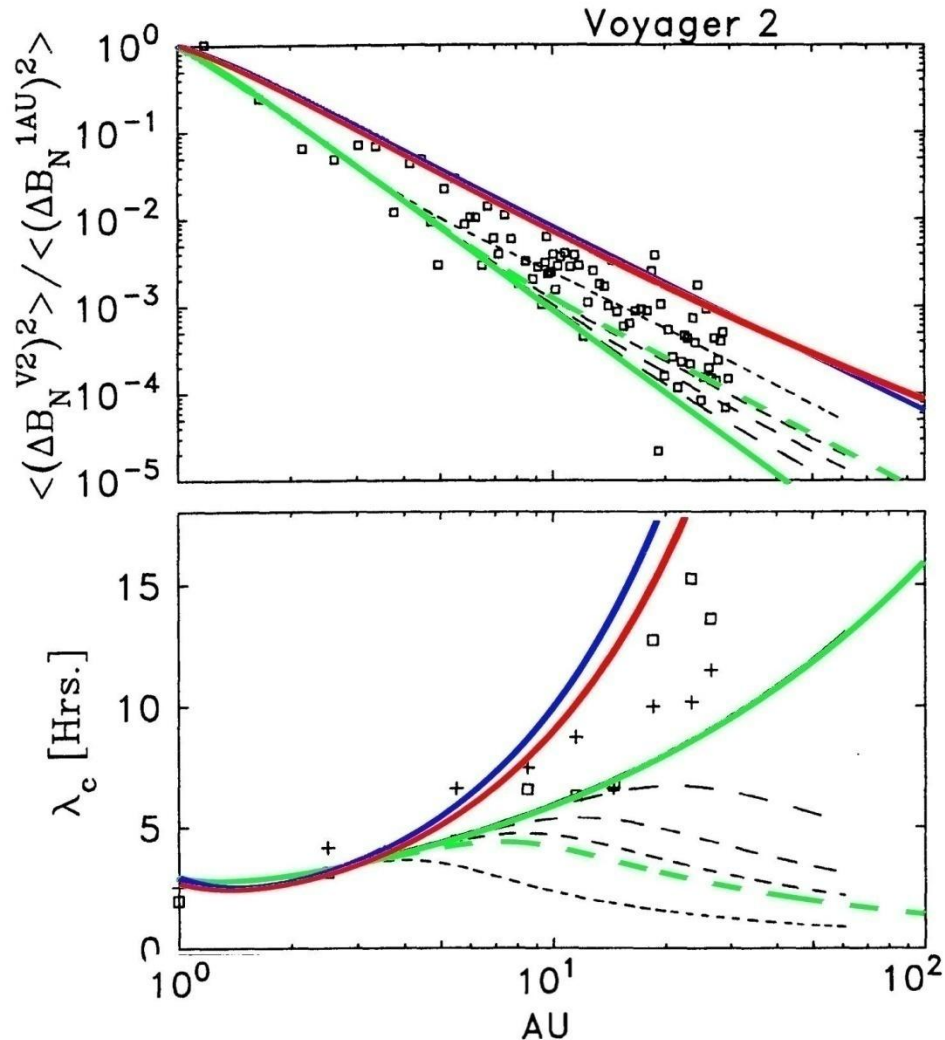


- Kolmogorov without Q
- - - Kolmogorov with Q
- IK without Q

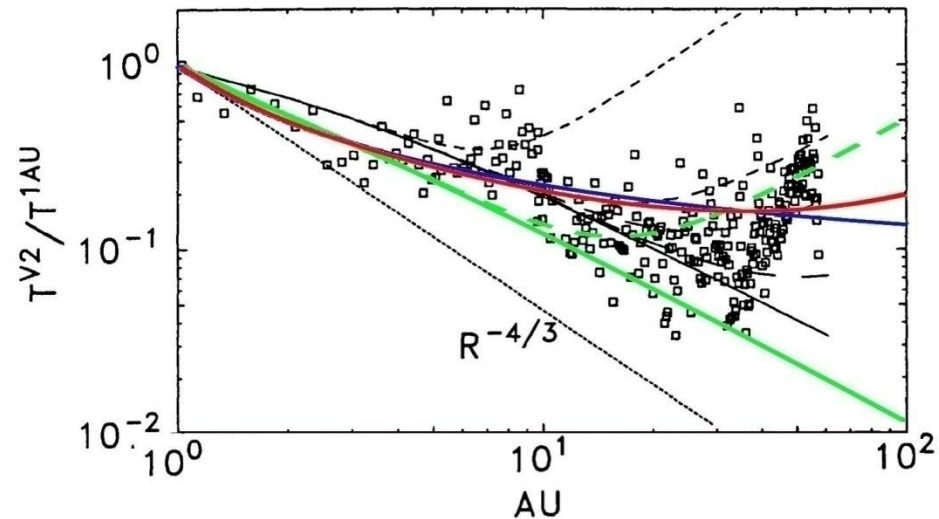


C.f. [Smith et al. 2001], with corrected temperature equation.

Comparisons with observations



- Kolmogorov without Q
- - - Kolmogorov with Q
- IK without Q
- IK with Q



C.f. [Smith et al. 2001], with corrected temperature equation.

Conclusion

- Although a solar wind model based on Kolmogorov cascade compares well with proton temperature observations when contributions from pickup ions are included, observations are also consistent with IK cascade, and are less sensitive to the contribution of pickup ions.
- Pickup ions generate less turbulence under IK cascade.
- The predictions of correlation length based on IK cascade appear to agree better with data than Kolmogorov cascade with pickup ions.
- Solar wind heating based on IK cascade is a possible alternative to Kolmogorov based theories and should be investigated more extensively.