Emergent signature of a global scaling of heat transport in fusion plasmas

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Motivation

In most common transport models both in fluid and plasma dynamics, the hierarchy of the moment equations is closed by applying the Boussinesq hypothesis that turbulent stresses are linearly proportional to mean strain rates. The reasoning behind this is the assumption of Markovian, Gaussian, uncorrelated stochastic processes which allow for a relaxation of the energy of the turbulent fluctuations to dissipative scales much the same way as molecular frictions similar to the Newton's law of viscosity. This implies for example in plasmas, the divergence of the heat flux can be defined as a local, diffusive process

$$\nabla\cdot Q(\mathbf{r},t)=\frac{\partial}{\partial \mathbf{r}}\left(\chi(\mathbf{r},t)\frac{\partial}{\partial \mathbf{r}}P(\mathbf{r},t)\right) \tag{1}$$

A fundamental limitation with this approximation is that it can not reproduce key features of nonlinear systems, that can display a tendency toward self-organisation. They can be non-local and intermittent in space and time, e.g., fluctuations can be bursty in time and be distributed sparsely in space, with turbulent patches intermixed with laminar ones. It is nowadays recognised that transport phenomena induced by turbulence must be interpreted in the framework of anomalous diffusion. Anomalous transport is characterised by non-Gaussian (e.g. exhibit power-law tails) self-similar nature of the PDFs of particle displacement, and the anomalous scaling of the moments. There is a wealth of experimental evidence that in fusion plasmas the nature of turbulent heat transport is anomalous, and non-local (non-diffusive) [1-6].

Non-local transport model

In order to go beyond the limiting assumptions made to obtain (1), we introduce the following generalised form for the divergence of the flux as:

$$\nabla\cdot Q_j(\mathbf{r},t)=D^{\alpha_j}_{|\mathbf{r}|}S_j p_j(\mathbf{r},t) \tag{2}$$

where α is the index of the corresponding fractional derivative [3]. *S* is the anomalous-diffusion transport coefficient with the dimensionality of $[L^{\alpha}/s]$. Thus, for α = 2, we will recover a similar diffusive model as (1), and for α = 1 we obtain a convective transport model. For α < 2 the transport is so-called super- diffusive while for α > 2 the transport is considered sub-diffusive.

Evaluation of α

To determine the values of the fractional index of the heat flux α through power balance analysis. To define αs (*j = e, i* indicates the species), we propose to make use of the Fourier representation of the energy conservation equation in the general form as (see Ref. [3]):

$$\frac{3}{2}\frac{\partial}{\partial t}\hat{p}_j(\mathbf{k},t)-|\mathbf{k}|^{\alpha_j}\hat{p}_j(\mathbf{k},t)=\hat{H}_j(\mathbf{k},t) \tag{3}$$

Here, we have introduced the pressure as $P_j = n_jT_j$, with *H* being the net heating due to Ohmic, NBI and RF heating minus the radiation losses. For simplicity we have assumed $S_j = 1$, which means that all the physics of collisional, neoclassical and turbulence processes, is contained within the fractional index α_j. Through power balance analysis using (3), we can find the following expression for α_j:

$$\alpha_j=\frac{\log\left(\frac{\hat{H}_j-(3/2)\partial_t\hat{p}_j}{-\hat{p}_j}\right)}{\log|\mathbf{k}|} \tag{4}$$

Evaluation of experimental data

The analysis is performed using a large dataset from the JETPEAK database [7] of the JET carbon (C) and ITER like-wall (ILW) experiments. The analysed dataset contains 1256 samples from 868 different plasma shots. Each sample is an average over a stationary state for 1 s; therefore, the time derivative of the pressure in the relation (3) is neglected. More details of the experimental data used can be found in Ref. [8].

Observations:

1) Electron and ion heat channels are mainly non-diffusive
2) The values of $\alpha_{e,i}$ cover a wide range from ≈ 0.5 and ≈1.5 due to the wide differences in the heating, fueling, and scenario schemes across these plasmas
3) a general convergence trend toward $\alpha_{e,i} \sim 1$ is observed with an increase in the total power
4) Given that α ~1, suggests that a convective transport model is more appropriate for the heat channel
5) Reduced levels of diffusive transport $\alpha_e < 2$, suggests that the decay rate of turbulence energy at smaller scales is less strong, thus contributions from small scales (e.g ETGs) may be higher than expected from a diffusive closure

The histograms of the fractional index gives the peaks of the distributions at around $\alpha_{e,i} \approx 0.8$ with the standard deviations are $STD_{\alpha e} = 0.17$ and $STD_{\alpha i} = 0.21$, see in Fig 2.

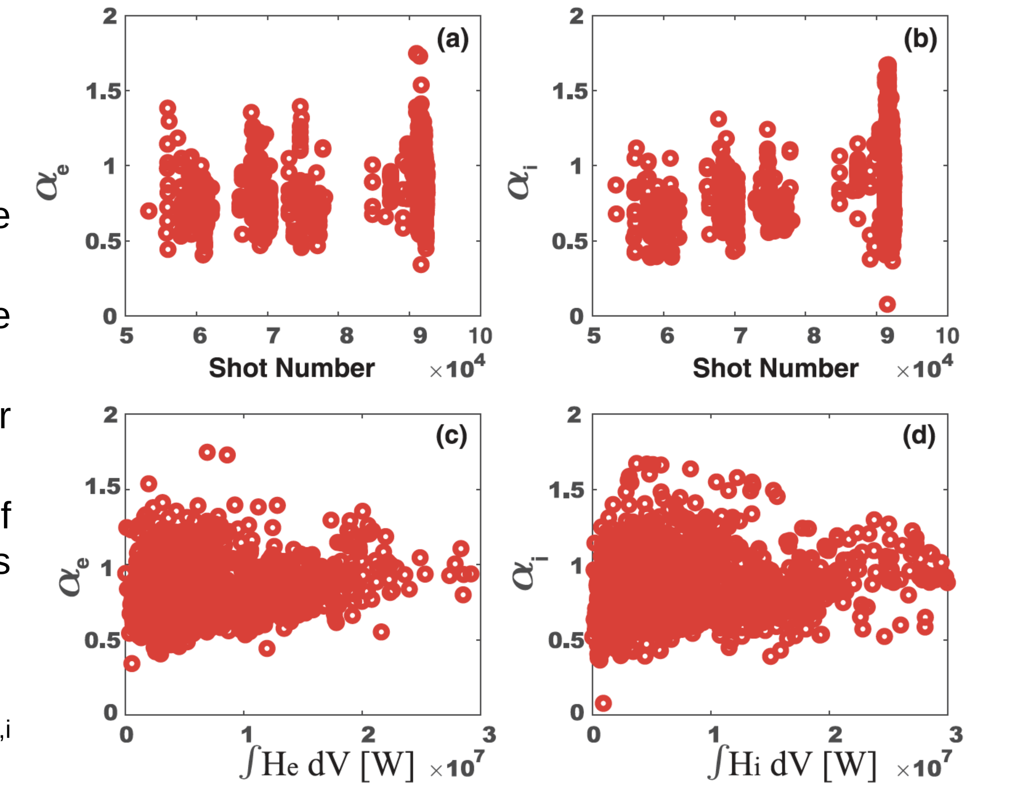

Fig1. The computed α_e [(a), (b)] and α_i [(c), (d)] as functions of the plasma shot number and the volume integrated net heating power for the selected JETPEAK dataset.

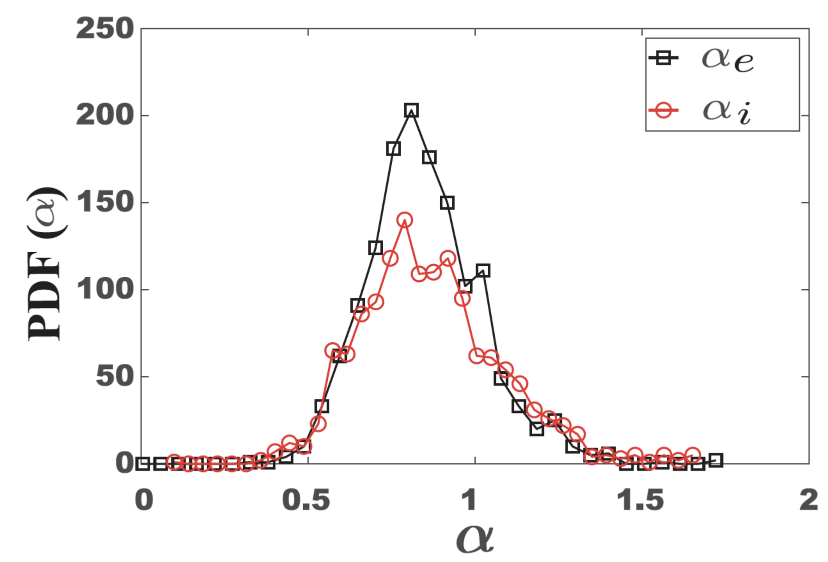

Fig2. The histogram of the computed α_e (black line with square symbols), and α_i (red line with circle symbols) for the selected JETPEAK dataset.

An example of the predicted pressure profiles for the # 92071 are shown in Fig. 3.

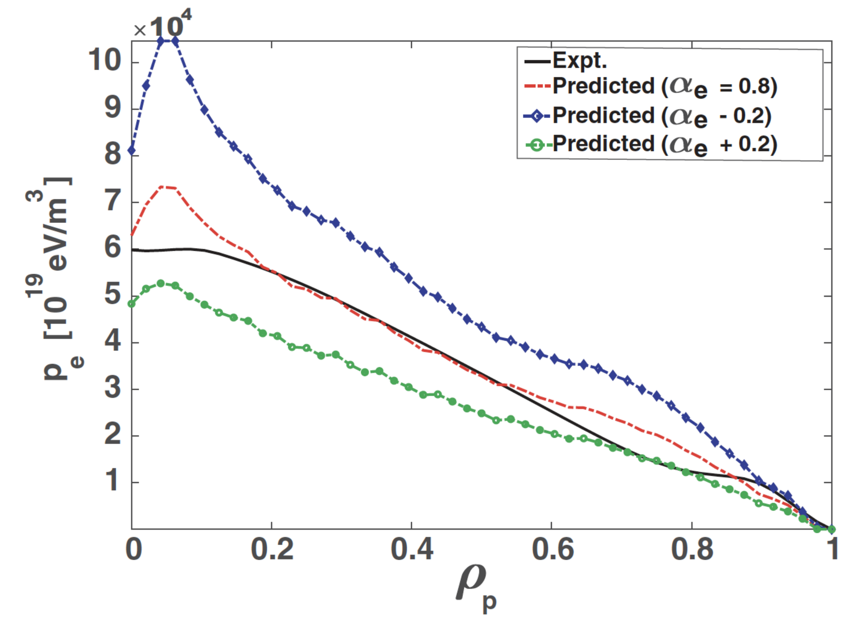

Fig3. Comparison of the experimental (black solid line) electron pressure profile versus normalized poloidal flux index ρp and the predicted profile following the global transport model in Eq. (5) (red dash-dotted line) for the plasma discharges #92071. The predicted pressure profiles with ±0.2 above (blue dotted line with diamond symbols) and below (green dotted line with circle symbols) the computed values of αe are also shown. This discharge is an ELMy H-mode pulse of hybrid type from ILW with 30 MW total input power (25 MW NBI + 6.6 MW ICRH) and regular type I ELMs during the steady-state phase.

Discussion

1) Both electron and ion heat flux show strong deviation from diffusive model.
2) A fractional closure model with α = 1.0 is expected to be more valid for heat flux than a diffusive model.
3) These results suggest that a global profile dependency between the net heating and the pressure profile in the JET plasmas exists which results in the relaxation of the pressure profiles to that of the heating deposition profile with a global decay rate, i.e., $|k|^{-\alpha}$, with an average α ≈ 0.8 over the selected database.
4) The 0-D model is a simple and easy to implement model for fast real time transport analysis.

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