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Statistical behaviour of a proxy of the entropy production rate of the solar photosphere

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Summary. — The solar photosphere provides an incomparable laboratory to study turbulent convection in a dissipative non-equilibrium system. The evaluation of the entropy production rate on the solar photosphere and its probability distribution are the key issues for studying the non-equilibrium dynamics of the solar convection. The local entropy production rate is not offhandedly measurable on the solar photosphere, but it can be easily evaluated using the vertical heat flux as a proxy, which is given by the product between the line-of-sight velocity and the surface temperature. In this work, we present some preliminary results on statistics of the local entropy production rate via the vertical heat flux, using line-of-sight velocity and temperature maps of the solar photosphere which are derived from high-resolution spectro-polarimetric data making use of the Center of Gravity Method and the Stefan-Boltzmann law.

1. – Introduction

In the great variety of natural systems in a non-equilibrium state, the turbulent solar convection is among the most interesting. Convection occurs in an internal layer of the Sun, the so-called convection zone, but the signature of this process is visible on the solar photosphere as a collection of bright structures, with a typical size of 1 Mm, surrounded by a network of dark lanes [1-4]. The high-resolution spectro-polarimetric data provided by modern ground-based and space telescopes allow us to investigate with unprecedented

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detail the dynamics of the photosphere and use the Sun as a natural laboratory to study the physical nature of the turbulent convection at high Rayleygh number [5-7]. Also, the photospheric motions can drive both the oscillation [8] and the reconnection [9] of small scale flux tubes. These two processes are the most invoked to address the Coronal heating problem.

Turbulent convection can be viewed as a dissipative process near a Non-Equilibrium Steady State (NESS) and the Sun provides an unequaled laboratory to perform the analysis of the entropy production rate characteristics in these systems. A reliable approach to characterize natural systems in a non-equilibrium state, is the analysis of their entropy production rate $\sigma(\vec{r},t)$ [10], which can be quantified as:

$$\sigma(\vec{r},t) = \sum_i J_i(\vec{r},t) X_i(\vec{r},t) > 0 \tag{1}$$

where $J_i(\vec{r},t)$ is a generic thermodynamic flux quantity and $X_i(\vec{r},t)$ is the associated generalized thermodynamic force or affinity, the i index accounts for the different contributions to the entropy production rate, and $\mathbf{r}$ is the position t is the time.

2. – Evaluating a proxy of the entropy production rate

Since the solar surface convection is a good example of NESS, following [11, 12], we can evaluate the local entropy production rate $\sigma(\mathbf{r},t)$ directly from the vertical heat flux $j_z(\mathbf{r},t)$, assuming that the transport occurs mainly in the vertical (radial) direction:

$$\sigma(\vec{r},t) \approx V_0 j_z(\vec{r},t) \nabla_z \left(\frac{1}{T}\right) \tag{2}$$

where V_0 is the volume over which the local properties are evaluated and $\nabla_z\left(\frac{1}{T}\right)$ is the vertical gradient of the temperature T which is responsible for maintaining the convection. Here, the local vertical heat flux is used as a *proxy* of the local entropy production rate and it can be computed as follows:

$$j_z(\vec{r},t) \approx v_{LoS}(\vec{r},t) \delta T(\vec{r},t) \tag{3}$$

where $v_{LoS}(\vec{r},t)$ is the plasma velocity along the line-of-sight (LoS) and $\delta T(\vec{r},t) = T(\vec{r},t) - T_0$, with T_0 being the average bulk temperature.

3. – Dataset and data analysis

The dataset used has been acquired on November 21st 2006 with the Interferometric BIdimensional Spectropolarimeter (IBIS [13, 14]), a high spectral resolution instrument based on Fabry-Perot interferometers, see e.g. [15-21], installed at the Dunn Solar Telescope (DST), located in National Solar Observatory (NSO), New Mexico. For this dataset, IBIS acquired the Stokes profiles in the spectral region containing the Fe I 630.15 nm and 630.25 nm lines and co-spatial broadband images in a nearby spectral region. The FoV imaged by the instrument is 40×40 arcsec^2, which corresponds approximately on the solar surface to 30×30 Mm^2, approximately at the solar disk center, so in our dataset the radial direction coincide with the LoS direction. The spatial resolution is 0.17 arcsec, corresponding to $\simeq$120 km on the solar surface, the time resolution is 89 seconds and the whole duration of the dataset is about one hour (41 time steps in total). The dataset has been calibrated using the IBIS pipeline [22]. For more details and information on the dataset, see [23-26].

The vertical heat flux has been evaluated from LoS velocity maps and temperature maps, using Eq.3. The LoS velocity maps are calculated using the Center of Gravity (CoG [27-29]) method applied to the Fe I 630.15 nm spectral line, as also discussed and compared to spectropolarimetric inversion results in [25]. The temperature maps are calculated using the Stefan-Boltzmann law [30, 31] applied to the broadband images. As customarily done in solar convention studies, the temperature and LoS velocity maps have been filtered through a subsonic $k_h - \omega$ filter, in order to remove the signal from the acoustic oscillations in the solar photosphere [32]. An example of vertical heat flux map J_1 is reported in Fig. 1 (left panel). We masked out the regions with an estimate magnetic flux greater than ≈ 50 Gauss (masked in black in the image), in order to analyze a quiet, i.e., non-magnetic, convective pattern. For further details on the LoS velocity and temperature maps computation, see [12]. To improve the statistics of our data, we compute a running average of j_z over time steps interval τ:

$$J_\tau(\vec{r}, t) = \frac{1}{\tau} \int_t^{t+\tau} j_z(\vec{r}, t')dt' \tag{4}$$

Therefore, hereafter, $J_1(\vec{r}, t)$ is the vertical heat flux for each temporal frame, $J_2(\vec{r}, t)$ is the average of the vertical heat flux between two temporal frames, $J_3(\vec{r}, t)$ between three temporal frames, and so on. The Probability Density Functions (PDFs), evaluated using the Kernel Method [33], for different value of J_τ are reported in Fig. 1 (right panel). The PDFs are clearly asymmetric, and this confirms that the solar photospheric turbulent convection is a non-equilibrium system, with a spontaneous production of entropy. In addition, we can also notice that the PDFs, going from J_1 to J_{29}, tighten, and this is a relevant behaviour that will be investigated in future works.

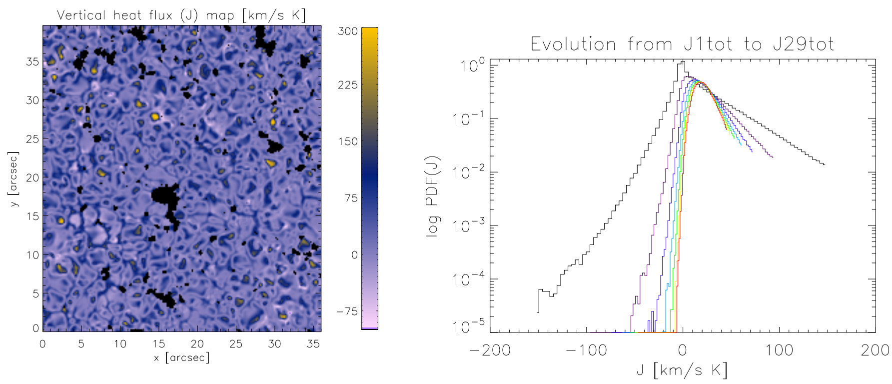

Fig. 1. – Left panel: sample vertical heat flux map. Black pixels mask those regions excluded from analysis. Right panel: PDFs of various J_z: black for J_1, purple for J_5, blue for J_{10}, light blue for J_{15}, green for J_{20}, yellow for J_{25} and red for J_{29}.

4. – Conclusions and future perspectives

In this work we estimate the entropy production rate of the solar turbulent convection, using the vertical heat flux as a proxy, evaluated using LoS velocity and temperature maps obtained from IBIS high-resolution spectro-polarimetric data. We show that the PDFs are evidently asymmetric, confirming that the turbulent solar convection is a system in a non-equilibrium state. These preliminary results, especially the tightening of the PDFs as τ increases, pave the way for future works, devoted to a more complete characterization of the non-equilibrium dynamical state of the solar turbulent convection.

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