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Evaluating a proxy of the local entropy production rate on the solar photosphere

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Abstract. 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 can be easily evaluated using the vertical heat flux as a proxy, which is given by a product between the line-of-sight velocity and the surface temperature. In this framework, the solar photosphere provides an incomparable laboratory to study turbulent convection in a dissipative non-equilibrium system near a steady state. 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 extracted from spectro-polarimetric data making use of the Center of Gravity Method and the simple black body radiation law.

1. Introduction

Most of the natural systems exist in a non-equilibrium configuration, showing very intriguing dynamics. A thermodynamic description of such systems requires the investigation of the entropy production rate [1], which is the physical parameter that quantifies the non-equilibrium state of these systems.

Among the uncountable non-equilibrium systems, the Sun is one of the most interesting, representing a natural laboratory to investigate the nature and the physics of turbulent convection with high Rayleigh number [2–4]. Nowadays, space and ground-based observations enable us to investigate this physical problem in an unprecedented detail, providing high-resolution images of several physical quantities at the Sun’s surface. This allow us to investigate in a great detail the dynamics of solar convection on the solar photosphere.

In non-equilibrium systems the measure of the entropy production rate is one of the key problems of non-equilibrium statistical thermodynamics, which presents many unanswered questions. Linear and non-linear non-equilibrium thermodynamics predicts that in non-equilibrium systems there is a non-zero spontaneous entropy production rate, which, according to the second law of thermodynamics, is a manifestation of the irreversible nature of such systems [1]. In non-equilibrium systems the entropy production rate is a function of position \mathbf{r} and time t , Which can be written as:



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

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, and the i index accounts for the different contributions to the entropy production rate. In treating the solar photospheric convection, we will concentrate on the vertical heat flux, $\vec{J}_q(\vec{r}, t)$, which will be estimated on the basis of the line-of-sight (LoS) velocity and the solar surface temperature.

Here, we present a preliminary evaluation of the statistical features of the entropy production rate in the solar photospheric layer, via the heat flux. Similar studies have been carried out in experimental laboratory physics. The statistical properties of the heat flux has been studied in a cylindrical cell filled with water in [5], and in a von Karman experimental setup and in a wind tunnel in [6].

2. The turbulent solar convection

The solar convection is a process that occurs in an internal layer of the Sun, the so-called convection zone (CZ). In this region, which is unstable according to the Schwarzschild criterion [7], a large fraction of the energy is carried by turbulent plasma flows, with the hotter plasma ascending and the colder plasma descending, driven by the surface entropy sink (radiative cooling). The signature of the convective pattern at the main energy carrying (granular) scale is visible in the solar photosphere as a collection of bright granules, with a typical size of 1 Mm, surrounded by a network of dark intergranular lanes [7–10]. If we define as CZ upper boundary the surface where the radial component of the upward velocity of the convective flows goes to zero [11], the CZ includes what is called the photospheric overshooting region.

The turbulent solar 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 in these systems.

The analysis shown in this work is performed by using the observations of a quiet-Sun region, i.e., a region excluding intense magnetic patches, in which we can assume that the convection pattern is not altered by the presence of magnetic field. In such an approximation, we can neglect the back-reaction of the magnetic field on the plasma motion, i.e., $\vec{J} \times \vec{B} \simeq 0$, and thus, the equations governing the solar convection in such quiet regions reduce to the standard fluid equations for heat-transport, i.e.,

$$\partial_t \vec{v} + (\vec{v} \cdot \nabla) \vec{v} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \vec{v} - \nabla \Omega \quad (2)$$

$$\partial_t T + \vec{v} \cdot \nabla T = \kappa \nabla^2 T \quad (3)$$

where Ω is the gravitational potential, ν is the plasma viscosity, κ is the temperature diffusivity coefficient, \vec{v} the velocity, T the temperature and p the pressure.

In this regime, the entropy production rate can be written in terms of the *heat flux*, \vec{J}_q , and the temperature gradient, ∇T , as follows [1],

$$\sigma = -\frac{1}{T^2} \vec{J}_q \cdot \nabla T, \quad (4)$$

so that assuming the temperature gradient to be constant, $\nabla T = \text{const}$, the heat flux provides a proxy of the entropy production rate. The last equation can be written also in the following form,

$$\sigma = \vec{J}_q \cdot \nabla \frac{1}{T}, \quad (5)$$

which will be used in the next Section to estimate the entropy production rate σ (see also [5] and references therein).

3. The evaluation of a proxy of the entropy production rate

The solar surface convection is a good example of phenomenon in a NESS. Thus, on the basis of the previous discussion and following [5], 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:

$$\sigma(\vec{r}, t) \approx V_0 j_z(\vec{r}, t) \nabla_z \left(\frac{1}{T} \right) \quad (6)$$

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.

Therefore, the local vertical heat flux is used as a *proxy* of the local entropy production rate and it can be computed as follows:

$$j_z(\vec{r}, t) \approx v_{LoS}(\vec{r}, t) \delta T(\vec{r}, t) \quad (7)$$

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.

4. Dataset and data analysis

The dataset used for this analysis has been acquired on November 21st 2006 with the Interferometric BIdimensional Spectropolarimeter (IBIS [12, 13]) installed at the Dunn Solar Telescope (DST), located in National Solar Observatory (NSO), Sacramento Peak, New Mexico. IBIS can perform imaging spectral scans of a selection of spectral regions with a resolution of $\simeq 4$ pm, and in its spectropolarimetry mode, it can also measure the polarization state of the incoming light, thus acquiring the Stokes profiles (the total intensity I , the excess of linear polarization Q and U , and the excess of circular polarization V) of the spectral lines. For this dataset IBIS measured the four Stokes profiles in the spectral region containing the Fe I 630.15 nm, and 630.25 nm, lines and broadband images in a nearby spectral region. The Field-of-View (FoV) of data is at the solar disk center, so in our dataset the radial direction coincide with the line-of-sight (LoS) direction. The FoV imaged by the instrument is 40×40 arcsec², which corresponds approximately on the solar surface to 30×30 Mm². The spatial resolution is 0.17 arcsec, corresponding to $\simeq 120$ km on the solar surface, the time resolution is 89 seconds (which is the time to perform a complete spectral scan) and the whole duration of the dataset is about one hour (41 time steps in total). For more details and information on the dataset, see [14–17]. The dataset has been calibrated using the IBIS pipeline [18]. In Fig. 1 (left panel) the spectral scanning of Stokes I parameter performed by the IBIS instrument is shown. Both spectral lines of interest are clearly visible.

The entropy production rate has been calculated from temperature and velocity maps, using Eq. 7. In detail, the temperature maps are evaluated using the black body radiation law [19, 20] applied to the broadband images. In particular, we computed the temperature maps from the Stefan-Boltzmann law as follows:

$$T(\vec{r}, t) = T_{eff} \sqrt[4]{C(\vec{r}, t)} \quad (8)$$

where $T_{eff} = 5780$ K is the average temperature of the solar photosphere [7] and the contrast has been defined as:

$$C(\vec{r}, t) = I(\vec{r}, t) / \bar{I}(t) \quad (9)$$

with $\bar{I}(t)$ being the average of the intensity I for each temporal frame.

We evaluated the LoS velocity maps using the Center of Gravity (CoG [21–23]) Method applied to the Fe I 630.15 nm spectral line, also discussed and compared with inversion techniques in [17], as follows:

$$v_{LoS}(\vec{r}, t) = \frac{\int I(\vec{r}, t) \lambda d\lambda}{\int I(\vec{r}, t) d\lambda} \quad (10)$$

where λ the wavelength and the integral is extended over all the wavelengths acquired during the spectral scan.

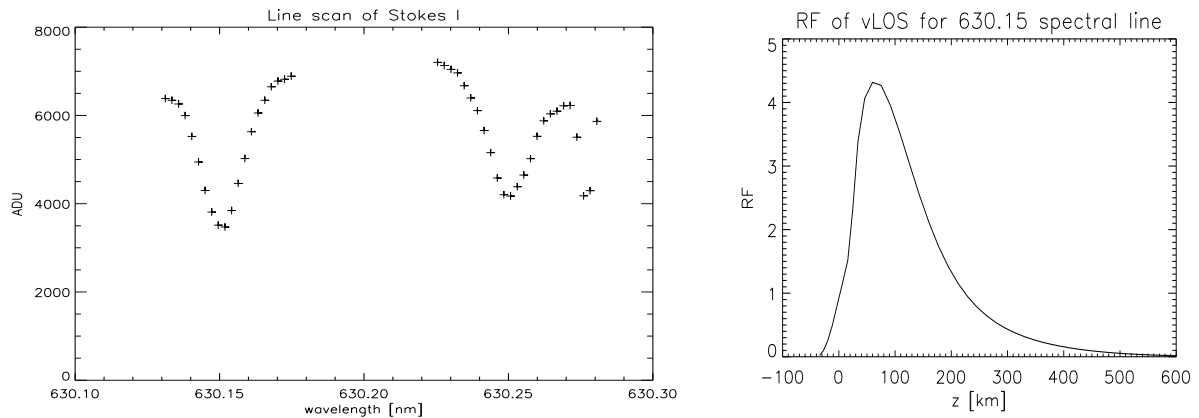


Figure 1. Left panel: Average IBIS scan of Stokes I profile of Fe I 630.15 nm and 630.25 nm spectral lines. At 630.28 nm is visible a telluric line due to absorption of water in the Earth's atmosphere. Right panel: average RF to v_{LoS} for Fe I 630.15 nm, spectral line.

Since we are using the Stefan-Boltzmann law applied to broadband images to compute the temperature maps, we assume that such temperature is associated with the base layer of the photosphere within the photon mean free path (≈ 100 km [24]). The association of a specific solar atmosphere layer with the LoS velocity maps instead deserves a more detailed treatment. To estimate the height of the v_{LoS} signal we are measuring, we make use of Response Functions (RFs) [25–27]. RFs tell us which is the atmospheric layer where the Stokes profiles are sensible to perturbation in the atmospheric parameters (such as temperature, LoS velocity, magnetic field intensity, and so on), and so the atmospheric height where the information encoded in the spectral line is mainly formed. Using standard solar atmosphere parameters, we are able to evaluate the RFs to v_{LoS} for each measured wavelength of the Fe I 630.15 nm spectral line [26]. By averaging those RFs, we obtain the RF to v_{LoS} tailored to our measure, shown in Fig. 1 (right panel). From the RF shape, using the full-width half-maximum, we can estimate that the layer associated with our v_{LoS} maps is $\approx 70^{+80}_{-50}$ km above the base of the solar photosphere. Therefore, the T and v_{LoS} signals we have measured, are associated to the same layer within

the measured errors, and we can safely combine them to compute a vertical heat flux J that can be associated with the same layer in the solar atmosphere.

As customarily done in solar convection 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 [28].

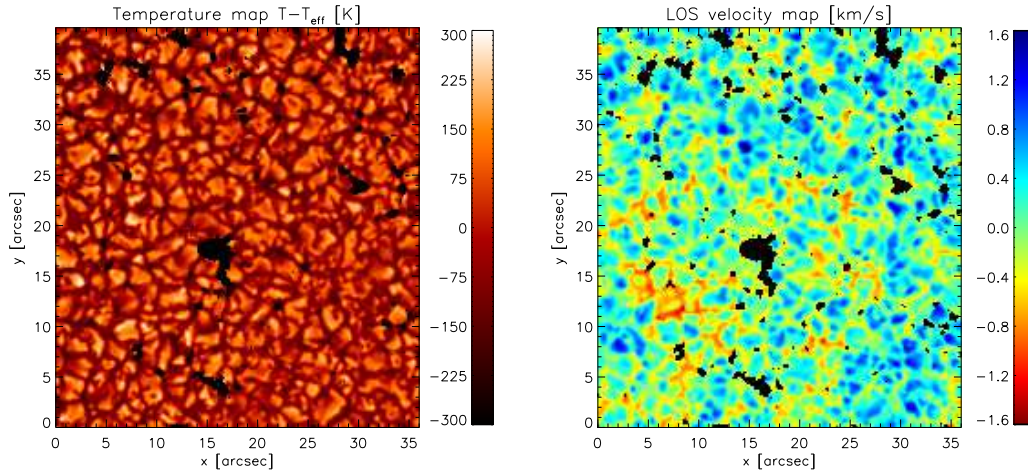


Figure 2. Left panel: a sample of a temperature map evaluated using the black body radiation law. The map shows the temperature fluctuations from the average temperature of the solar photosphere (T_{eff}). Right panel: the co-temporal LoS velocity map evaluated using the CoG method. Black pixels mask those regions excluded from our analysis because they have magnetic field intensity greater than 50 Gauss.

Using the polarimetric signal in the Stokes V parameter, we masked out the region with an estimate magnetic flux greater than ≈ 50 Gauss (black regions in Figure 2 and left panel of 3), in order to analyze a quiet, i.e., non-magnetic, region.

An example of the map of the vertical heat flux J , evaluated with Eq. 7 is reported in Fig. 3 (left panel). The histogram of the vertical heat flux values for all the time steps is reported in Fig. 3 (Right panel). The distribution of J is visibly asymmetric. This confirms that on the solar photosphere there is a spontaneous and positive production of entropy, typical of non-equilibrium systems.

5. Conclusion

In this work we investigate the entropy production rate on the solar photosphere using the vertical heat flux as a proxy. The latter was evaluated using temperature and LoS velocity maps retrieved from broadband images and spectro-polarimetric data using the black body radiation law and the CoG method, respectively.

We show that the observed distribution of the vertical heat flux is asymmetric and this suggests that the solar convection represents a natural non-equilibrium system, characterized by a non-zero entropy production rate.

The preliminary results we obtained pave the way towards future analyses reaching a complete characterization of the non-equilibrium dynamical state of solar photospheric convection.

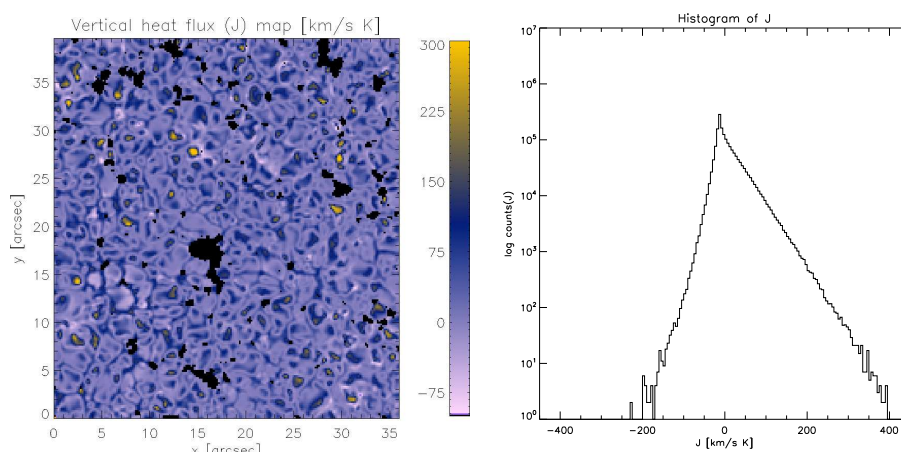


Figure 3. Left panel: sample vertical heat flux map. As above, black pixels mask those regions excluded from analysis. Right panel: histogram of the vertical heat flux for the whole dataset.

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