Solar and Stellar Magnetic Fields: Origins and Manifestations
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Reversibility of Turbulent and Non-Collisional Plasmas: Solar Wind

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Abstract. We have studied turbulent plasma as a complex system applying the method known as *Horizontal Visibility Graph* (HVG) to obtain the *Kullback-Leibler Divergence* (KLD) as a first approach to characterize the reversibility of the time series of the magnetic fluctuations. For this, we have developed the method on *Particle In Cell* (PIC) simulations for a magnetized plasma and on solar wind magnetic time series, considering slow and fast wind. Our numerical results show that low irreversibility values are verified for magnetic field time series associated with Maxwellian distributions. In addition, considering the solar wind plasma, our preliminary results seem to indicate that greater irreversibility degrees are reached by the magnetic field associated with slow solar wind.

Keywords. Plasmas, turbulence, methods: statistical.

1. Introduction

A particular case of turbulent and non-collisional plasma is solar wind. The study of the dissipation of these processes allows characterizing the behavior of fast or slow solar wind. To understand its dynamics from another perspective, this plasma has been modeled as a complex system, studying the information delivered in time series, since the analysis of these results is a useful tool to characterize the behavior of any system.

In statistical mechanics, the Horizontal Visibility Graph (HVG) technique has been used to measure the temporal irreversibility of data sets produced by processes that are not in equilibrium, getting information on the production of entropy generated by the physical system (Lacasa *et al.* 2012). The HVG method has been applied to obtain the Kulback Leibler Divergence (KLD) or relative entropy value and thus analyze the degree of irreversibility of magnetic fluctuations generated by the system, understanding a high degree of irreversibility as a chaotic and dissipative system (Suyal *et al.* 2014). Here we show preliminary numerical results on the use of HVGs to two plasma systems Namely, numerical Particle in Cell simulations, and the solar wind. In both cases we computed the KLD based on magnetic field time series, as a first approach to the study of the reversibility of magnetized collisionless plasma systems in astrophysical environments.

In this sense, we have used the PIC simulation method to generate different types of plasmas in order to understand the degree of the irreversibility KLD as a parameter that can be related to the shape of the particles velocity distributions considering the well-known κ distributions (Viñas *et al.* 2014). In addition, we also applied the algorithm to study the reversibility of magnetic field time series associated obtained by the Wind mission in the solar wind between 01-01-1995 and 30-06-1995, focusing on the possible relation between the KLD value and solar wind speed. This article is organized as follows: in section 2 we present the HVG graph and the calculation of the KLD. Section 3 presents our main results, and section 4 is dedicated to conclusions and discussion.

2. The Horizontal Visibility Graph

The complex network is constructed by assigning a node to each data in the series, and a height according to its value. Then, two nodes are connected if a horizontal line can be drawn on the time series graph, such that it links them and does not intersect any intermediate height.

To characterize this network, a stationary process $X(t)$ is said to be statistically time reversible if for every N the series $\{X(t_1), ..., X(t_N)\}$ and $\{X(t_N), ..., X(t_1)\}$ have the same joint probability distributions $P_{out}(k = k_{out})$ and $P_{in}(k = k_{out})$, where k_{in} and k_{out} correspond to the input and output connections in each data, respectively (Lacasa *et al.* 2012).

The KL Divergence is constructed with the degree distributions, understood as a distance between P_{in} and P_{out} to assess the difference between both distributions. It is defined by

$$D[P_{out}(k)||P_{in}(k)] = \sum_k P_{out}(k) \log \frac{P_{out}(k)}{P_{in}(k)} \tag{2.1}$$

In eq. 2.1 we have used the convention $0 \log \frac{0}{0} = 0$ and the convention $0 \log \frac{0}{q} = 0$ and $p \log \frac{p}{0} = \infty$. Thus, if there is any symbol $x \in X$ such that $p(x) > 0$ and $q(x) = 0$, then $D(p||q) = \infty$. Otherwise, if $D \to 0$, the system has a low degree of irreversibility (Thomas & Cover 2006).

3. Results

3.1. *Particle-In-Cell Simulations*

First, we apply the HVG method to study time series of magnetic fluctuations obtained from PIC simulations, considering thermal (Maxwellian) and non-thermal (kappa) distributions (please see Viñas *et al.* (2014) for details about the simulations).

Considering the Maxwellian distribution and kappa distributions with different κ values we run the simulations to generate a magnetic energy density (B^2) time series (see Fig. 1 left panel). Then, the KLD, designated by D, is calculated for each case.

Fig. 1 (Maxwellian distributions correspond to velocity distributions when $\kappa \to \infty$) is shown that the dissipative degree of the system increases as the value of κ decreases. The HVG method is able to detect and measure the different behaviors of each distribution, even when magnetic time series seem similar among themselves. These results suggest a relation between the KLD and the κ value.

3.2. *Solar Wind*

We also used the HVG and computed the KLD considering magnetic field time series measured by the Wind spacecraft in the solar wind. The fast solar wind originates from coronal holes (Feldman *et al.* 1976) although the slow wind originates from above active regions on the Sun. (Krieger *et al.* 1973; Woo & Martin 1997). In order to study possible correlations between the degree of irreversibility of magnetic fluctuations (see Fig. 3 left panel) with the solar wind speed, we applied the HVG on time intervals associated with slow or fast solar wind.

Left and right panels in Fig. 2 show electron and proton bulk velocity measured by Wind during 1995, respectively. To separate between slow and fast streams we considered a threshold value of 500 km/s. In addition, we also discarded data between 450 km/s and 550 km/s so we can be sure that each interval contains only data from slow or fast solar wind exclusively. With this procedure, 46 time windows (24 with slow wind data, and 22 with fast wind data) were created, and the KLD value was computed for each of them.

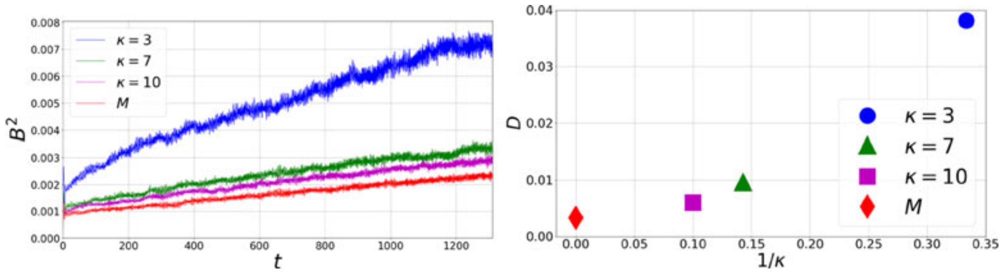

Figure 1. (left) Magnetic field obtained from PIC simulations for Maxwellian and kappa distributions considering different values of the κ parameter. Magnetic field and time values are expressed in arbitrary units. (right) KL-Divergence of magnetic field for different kappa distributions. The values for D are 0.0033 (Maxwellian), 0.0060 ($\kappa = 10$), 0.0094 ($\kappa = 7$) and 0.0381 ($\kappa = 3$).

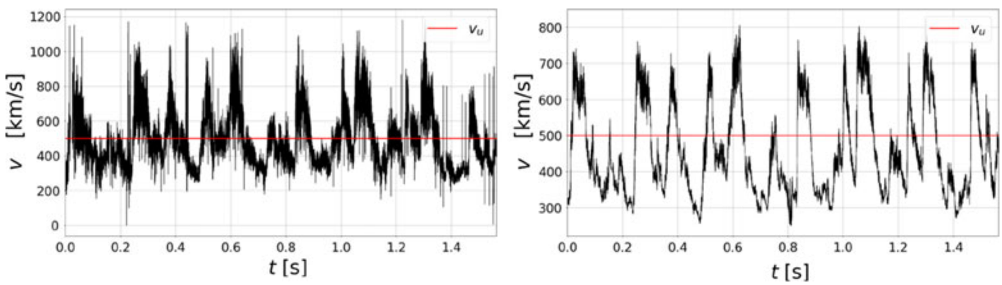

Figure 2. (left) electron and (right) proton bulk velocity magnitude. The red line separates slow and fast wind intervals.

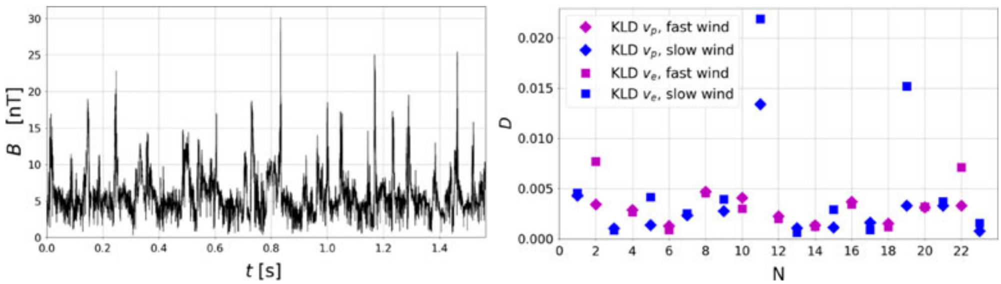

Figure 3. (left) Magnetic field magnitude. Measurements made by the Satellite Wind, data obtained from NASA CDAWeb database from 01-01-1995 until 30-06-1995. (right) KL-Divergence of magnetic field in matching time windows of slow and fast wind, protons and electrons.

Fig. 3 (right) show the results separating the 46 time windows between slow (blue) and fast wind (purple) intervals, and according the electron (squares) and proton (rhombuses) bulk velocity. It is observed that for high values of divergence, or a high degree of irreversibility, magnetic field is associated with slow solar wind, which tends to present a more chaotic behavior. However, for fast stream intervals the relation is not as clear.

4. Discussion and conclusions

In this study we have applied the method known as Horizontal Visibility Graph (HVG) to obtain the Kullback-Leibler Divergence as a first approach to study the reversibility on magnetic fluctuations, modeling turbulent plasma as a complex system. We have

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developed algorithms to build HVGs starting from magnetic field time series obtained from Particle In Cell simulations of collisionles magnetized plasmas, and also on solar wind magnetic time series measured by the Wind spacecraft, considering slow and fast wind streams.

Considering PIC simulations, low irreversibility values are verified for magnetic field simulations associated with Maxwellian distributions, and that the KLD value increases for decreasing κ value. Also, for the case of solar wind data, our preliminary resuls show that greater irreversibility degrees are reached by the magnetic field associated with slow solar wind. Our results seem to indicate that the shape of the particle distributions and macroscopic plasma parameters like the solar wind speed are related with the KLD value, and therefore the reversibility of the magnetic field time series, suggesting that complex networks may be a valuable alternative tool to study and characterize turbulent plasma systems.

We expect that understanding and characterizing these complex systems properties on the basis of in situ measurements could be helpful to study the characteristics of stellar winds only reachable through distant observations.

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