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RELATIVE ORDER OF AURORAL STRUCTURE DURING SUBSTORM ACTIVATION

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Abstract. The last decade complexity in magnetosphere-ionosphere plasma has been discussed in numerous papers. The most popular approaches are based on turbulence or/and self-organized criticality paradigms. However, there is no clear evidence that the dynamics during the events analyzed represents organization, and not disorganization. The problem is that the magnetosphere-ionosphere system is an open, non-equilibrium system; therefore classical thermodynamics is not directly applicable. Here we use an approach based on the S-theorem by Yu. L. Klimontovich. This approach allows us to compare the order which characterizes the current (non equilibrium) state of the system to experimental data. The considered characteristic is an analogy of entropy extended to non-equilibrium states. Television observations of the auroral structure during substorm activation at the Barentsburg observatory (Svalbard) have been used as a data set. Dependence of the order on the spatial scale has been analyzed. Our main finding is that the order of the aurora increases during substorm activations.

1. Introduction

Signatures of complex dynamic behavior are ubiquitous in space plasma. Often they are refereed to as 'turbulence', meaning strong coupled fluctuations at wide range of scales [Borovsky et al., 1997, Borovsky and Funsten, 2003]. However even for classical turbulent flows theories are incomplete [Frisch, 1995]. Recently, the self-organized criticality (SOC) paradigm was suggested to describe the plasma complexity [Angelopoulos et al., 1999]. As yet, there is no known direct theoretical correspondence between SOC and turbulence, but there are manifestations of both SOC and turbulence in the same data sets [Kozelov et al., 2004; Kozelov and Rypdal, 2007; Uritsky et al., 2006]. Therefore, it would be important to demonstrate that the dynamics during these events represents organization, and not disorganization. The problem is that the turbulent systems (like the magnetosphere-ionosphere system) are open and non-equilibrium, and thus classical thermodynamics is not directly applicable. The great diversity in statistical distributions observed in complex systems is anomalous from the viewpoint of traditional statistical mechanics based on the Boltzmann-Gibbs-Shannon entropy. Consequently, some generalization is needed.

In this contribution we use an approach based on the S-theorem by Yu. L. Klimontovich [1996]. This approach allows us to compare the order which characterize the current (non equilibrium) state of the system with experimental data. The considered characteristic is an analogy of entropy extended to non equilibrium states. The main idea of the approach is that the order of two different states of an open system should be compared for the same average energy of the system. One of the states should be selected as a state of 'physical chaos' and the distribution characterizing the state should be 'heated' to the same average energy as the second state. Then, the entropy of the states can be compared.

The approach has been applied to the auroral structure observed at the Barentsburg observatory (Svalbard) during substorm transients.

2. Formalism

The criterion of relative order for the states of a system was developed in the works of Yu. L. Klimontovich [1995-1998]. Here we briefly reproduce the formalism needed to apply the criterion to an experimental data set.

Let a system state be described by the distribution function $f(x, a)$, where x is an intrinsic parameter of the distribution and a is a governing parameter. Let us assume that the state with $a=a_0$ is a chaotic state and we want to compare the order of two states with a_0 and $a_0+\Delta a$ for $\Delta a>0$. The two distributions correspond to the states:

$$f_0 = f(x, a_0),\quad f = f(x, a_0+\Delta a),$$

where $$\int f_0 dx = \int f\, dx = 1 . \qquad (1)$$

From the distribution f_0 we can find the function $H_{eff} = -\ln f_0$, which will play the role of an effective Hamiltonian. In the most common cases the average value of the effective energy obtained by the distributions (1) depend on Δa. Let us consider re-normalization to the same value $\langle H_{eff}\rangle$ by a re-normalized function $\tilde{f}_0$. The function we consider as a canonical distribution:

$$\tilde{f}_0(x, a_0, \Delta a) = \exp[D^{-1}(\Delta a)(F(D) - H_{eff}(x, a_0))] \qquad (2)$$

$$\int \tilde{f}_0 dx = 1$$

The dependence of the effective free energy $F(D)$ on the temperature D is determined from the normalization condition for $\tilde{f}_0$. The dependence of the effective temperature D of the governing parameter Δa can be found from the equation

$$\int H_{eff}(x,a_0)\tilde{f}_0(x,a_0,\Delta a)\,dx =$$
$$= \int H_{eff}(x,a_0) f(x,a_0+\Delta a)\,dx\,, \quad (3)$$

which is a condition of constant average value of effective Hamiltonian. The solution of the equation gives us the function

$$D(\Delta a); \qquad D(\Delta a)|_{\Delta a=0} = 1, \quad \Delta a \geq 0 \qquad (4)$$

If $D(\Delta a)>1$ for $\Delta a\neq 0$ then the state with $a_0+\Delta a$ is more ordered than the state with $a = a_0$, which we select as a state of physical chaos. However, to test this assumption the effective temperatures for processes in forward (from a_0 to $a_0+\Delta a$) and backward (from $a_0+\Delta a$ to a_0) directions should be compared. If the effective temperature for the backward process is less then 1, then the selection of the chaos state is valid. If the effective temperature in both cases is >1 then the self-organization evolves in the direction for which higher value of the temperature is obtained.

Now the difference of entropies can be found by distributions $\tilde{f}_0$ and f as:

$$L_S = \tilde{S}_0 - S = \int f \ln(f/\tilde{f}_0)\,dX \geq 0 \qquad (5)$$

This value can be used as a numerical characteristic to compare the relative order of the system states.

3. Experimental data set

As an experimental data set we will use the set of auroral images obtained by television observation at the Barentsburg (Svalbard) during the night 19-20 January, 2001. The data set was already described in previous papers [Kozelov et al., 2004; Kozelov and Rypdal, 2007]. Here our study is focused on the dynamics of the magnetosphere-ionosphere system during the observed disturbance; therefore we use the time t as a governing parameter and consider two types of distributions to characterize the observed system state:

1) $P(t, I)$ - probability distribution of an intensity I in the central region (~200x200 km) of the all-sky TV frame, calculated from occurrence number of pixels vs. auroral intensity, see figure 1. The intensity of the frames has been additionally calibrated to the same position of the distribution maximum.

2) $P(t, s, \Delta I)$ - probability distribution of intensity variation $\Delta I= |I(x)-I(x+s)|$ for all pairs of pixels separated by a distance s in the same region as 1). We consider the distributions for spatial separations s corresponding to spatial scales from 3 to 72 km.

All distributions have been summed in 20 s intervals to improve statistics. The cells with zero values have been filled by small finite values to avoid numerical problems. We found that this procedure does not influence the results significantly.

As a state of 'physical chaos' we select the state without aurora in the considered region of the sky. The corresponding distribution of the first type, $P_o(t, I)$, has been obtained by averaging of the distributions during the first 100 seconds of the interval under consideration. The $P_o(t, I)$ distribution is shown in figure 1 in the curve marked as 22:10:00UT. We found that for this state there is very weak dependence of the distribution of intensity variation, $P_o(t, s, \Delta I)$, on the scale s [Kozelov and Rypdal, 2007]. Therefore, this distribution can also be used as a referenced state to compare the ordering at different spatial scales.

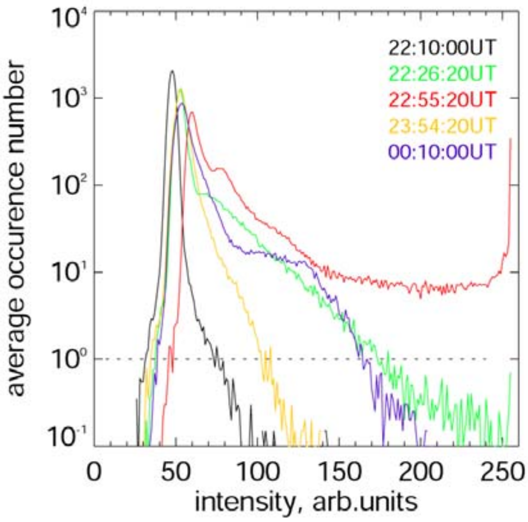

Fig.1. Occurrence number of pixels vs. auroral intensity averaged in 20-s intervals, beginning from the marked time. 1-pixel occurrence level is shown by dashed line.

4. Results

The north-south keogram of the aurora obtained from the TV data set is shown in the top panel of the figure 2. (The black intervals are the data gaps.) Other panels of the figure 2 present the results of the order analysis.

Evolution of the effective temperature (see equation 4) calculated relative to the selected state of 'physical chaos' is shown in the second panel as a solid curve. The $D(t)$ curve is located above the line D=1, which means the selection of the 'chaotic' state has been done correctly. The effective temperature for the backward direction of the temperature calculation by equations (2)-(3) is shown by the dotted curve. One observes that $D(t)$ <1 for the backward process, which is an additional test supporting the selection of the 'chaotic' state, and we can estimate the entropy difference relative to the selected 'chaotic' state by means of equation 5.

The next panel of figure 2 presents the evolution of the entropy difference estimated from the probability distributions of auroral intensity. The entropy difference is non-negative during the entire period considered. The entropy difference increases during activation of aurora; this means that the relative order of the aurora is increased.

Using the probability distribution of intensity variation, $P(t, s, \Delta I)$, to characterize the system state we can obtain more details about the order at different spatial scales. The distributions for time intervals without aurora are also satisfy the conditions for 'physical chaos' (the plots for corresponding evolution of effective temperature are not shown here, but it looks similar to the second panel of figure 2). As we discussed in [Kozelov and Rypdal, 2007], the probability distribution of intensity variation in the TV all-sky frames without aurora have very weak dependence on scale *s*. Therefore, it is possible to compare not only distributions for the same spatial scale, but for different scales. The bottom panel of figure 2 presents the evolution of the entropy difference estimated from probability distributions of auroral intensity variations at scales 3, 12, and 72 km, demonstrating that the entropy difference is larger for larger spatial scale.

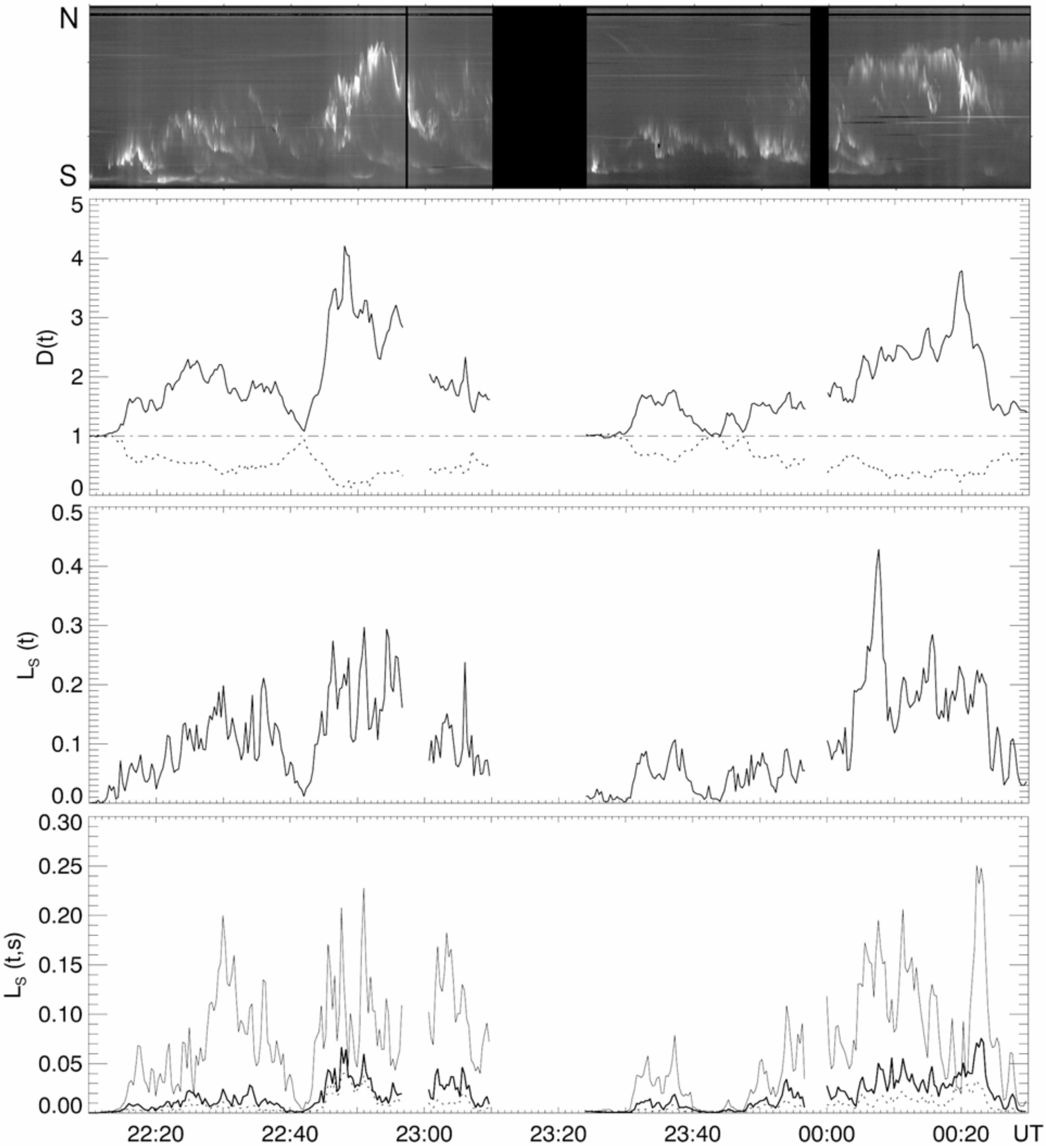

Fig.2. Auroral events on 19-20 January, 2001.Top panel: the N-S keogram of the all-sky TV images. Second panel: evolution of effective temperature calculated for direct (solid line) and backward (dotted line) processes, dot-dashed line - temperature of the state of 'physical chaos'. Third panel: evolution of the entropy difference estimated by probability distributions of auroral intensity. Bottom panel: evolution of the entropy difference estimated by probability distributions of auroral intensity variations at scales 3, 12, and 72 km are shown by dotted, solid thick and solid thin lines, correspondently.

5. Discussion

Here we have considered the data set of optical observations which was previously used in papers [Kozelov et al., 2004] and [Kozelov and Rypdal, 2007]. The data set was analyzed by application of a spatiotemporal technique of selection of avalanche-like transients, and it was found that the statistical distributions of the characteristics of these transients is consistent with the existence of SOC-like states in the magnetosphere-ionosphere plasma [Kozelov et al., 2004]. However the same data set shares some intermittency features which are known to be fundamental characteristics of classical turbulence [Kozelov and Rypdal, 2007]. In the present paper, using information about spatial distribution of the auroral luminosity, we have demonstrated that the thermodynamic approach based on the S-theorem by Yu. L. Klimontovich can be applied to estimate the relative order of the auroral structure. The obtained increase of the order of the aurora during substorm activation is in qualitative agreement with Klimontovich' conclusion that the turbulent state is more ordered than a laminar state for flows.

There are some methodological questions that are still not clarified. The important advantage of the Klimontovich approach is that the experimental distributions can be used. However, in practice the experimental distribution cannot provide a full description of a complex system. The spatial distribution of the auroral intensity is an analogy of a dissipation field. In [Yahnin et al., 2006] it was shown that the total energy dissipated in the night side of the auroral oval during the expansion phase corresponds well to the energy stored during preceeding phase. Can we use the restricted information (only dissipation field) to characterize the state of the entire system? Another unsolved problem is the connection between local and global observations. This is an important issue since the ground-based all-sky camera observes only small region of whole auroral oval.

These questions should stimulate further studies of model data sets, generated by SOC and turbulent systems.

6. Discussion and conclusions

The approach based on the S-theorem by Yu. L. Klimontovich has been applied to estimate the relative order of the auroral structure observed during substorm transients. According to the criterion, the order of the aurora increases during the substorm activation. This finding can be interpreted as a manifestation of increased (self-)organization (order) of the magnetosphere-ionosphere plasma in the corresponding region during the substorm transient. The changes of the order are larger at larger spatial scales.

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