"Physics of Auroral Phenomena", Proc. XXIX Annual Seminar, Apatity, pp.48-51, 2006

Polar Geophysical Institute

INTERMITTENCE IN AURORAL FLUCTUATIONS DURING SUBSTORM

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Abstract. The data of television (TV) observations at the Barentsburg observatory (Svalbard) have been analyzed to search the statistical features of auroral fluctuations during an expansion phase of substorm. The shape of the probability density function (PDF) of the auroral fluctuations was examined in different spatial scales. We found that the observed PDFs have a non-Gaussian shape. The generalized structure function (GSF) for the auroral luminosity fluctuations has been analyzed to determine the scaling properties of the higher (up to 6) order moments. Evolution of the scaling indices during the considered event is presented. The obtained scaling features of optical fluctuations for auroral structures are interpreted as a signature of intermittent turbulence in the magnetosphere-ionosphere plasma.

1. Introduction

During the last decade there have been many indications, that the magnetospheric-ionospheric system (MIS) can behave similarly to the systems which have a so-called self-organised critical state (*Consolini*, 1997; *Vörös*, 1991; *Milovanov et al*., 1996; *Uritsky and Pudovkin*, 1998; *Uritsky et al*., 2002; *Kozelov et al*., 2004). At least a part of these indications were alternatively interpreted in terms of intermittent turbulence (Borovsky and Funsten, 2003). It is necassary to remind that SOC concept was also applied to describe the intermittency in the Earth's plasma sheet (*Angelopoulos et al*., 1999). However, the turbulence in the magnetosphere-ionosphere plasma have some peculiarities, which differ from the known theoretical models (*Borovsky and Funsten*, 2003). *Chang* (2004) proposed a scenario that induces an intermittent turbulence by a dynamical topological complexity that results from the nonlinear evolution of multiscale coherent structures. The individual plasma processes are incorporated by this scenario in a uniform SOC-like state.

In this paper we have used the same dataset which was previously analyzed in *Kozelov et al.*, (2004) by spatio-temporal techniques of selection of avalanche-like transients. Now we present a description of statistical features of aurora luminosity fluctuations during the substorm disturbances by characteristics that usually applied to turbulence flows: probability density function (PDF) and generalized structure function (GSF).

2. TV observations of aurora

Barentsburg observatory is located in Svalbard (78.1°N, 14.24°E, 75.17°MLAT, 112.1°MLON), the quiet night-time auroral oval being observed near its southern horizon. This location is very favorable for observations of poleward motion of aurora during the expansion phase of substorm. We have chosen for the analysis the same event during the evening of January, 19-20, 2001, which had been previously analyzed by another technique (*Kozelov et al*., 2004).

The digitized video frames (5 frames per second) from television all-sky camera (TV ASC) are superposed and averaged over 1 s to reduce the noise level. The central part of the frames, ~200×200 km^2, where the projection distortions are not significant, is used for the analysis. Here we neglect the deviations of spatial resolutions and other distortions of the ASC image, assuming that the average spatial resolution of TVASC in the considered field of view is ~1.5 km.

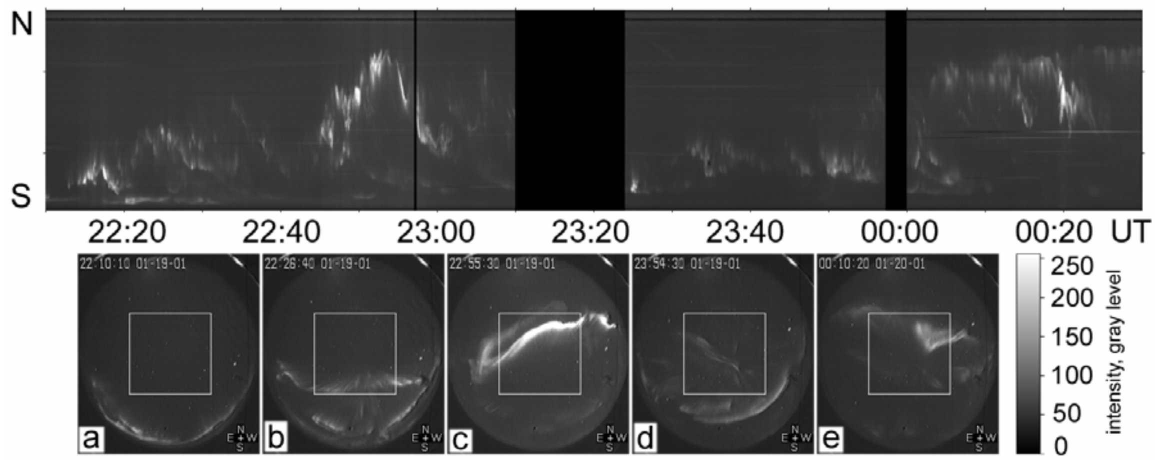


Figure 1. Auroral structures during the event of January,19-20, 2001. Top panel: north-south keogram obtained from TVASC images. Bottom panel: several examples of the TVASC images. The considered part of fied of view is ticked at the vertical axes of the keogram and is marked with a white frame in the images.

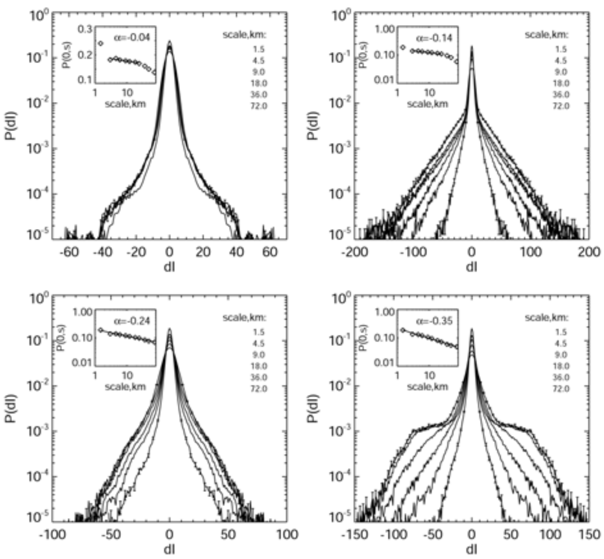


Figure 2. Dependence of PDF of intensity fluctuation on spatial scale for several 20-s intervals starting from: a - 22:10:00; b - 22:26:20; c - 23:54:20; d - 00:10:00. Insets: symbols - maximum values of the PDF, line - the least squre power law approximation as $P(0,s) \propto s^{\alpha}$. Descrepancies of the α values are less than 0.01.

Figure 1 presents a keogram for the considered event and several TV images from the set. The central part of the frames used in this study is marked with white rectangle. The Universal Time (UT) and the date of observation are shown on top of each image. The images illustrate various types of auroral structures observed during the event. The image 'a' is an example with no aurora in the considered field of view. The structure in the image 'b' is weak rayed arcs; the 'c' is a bright arc which is developing somewhat further in spiral; the 'd' and 'e' are corona-like structures. The auroral intensity distributions during short 20 seconds intervals included the images chosen as examples for the detailed analysis in this paper.

3. PDF of auroral fluctuations

A more detailed information may be obtained through the analysis of the probability density functions (PDFs) of a two-pixel variation δI of the intensity. We consider a two-pixel variation $\delta I = I(p+s)-I(p)$ of the intensity I, for the given vertical and horizontal distance s in each frame. Each pair of pixels is used 2 times in the statistics with different sign of δI, therefore the considered PDFs are symmetrical by definition. The pairs from 20 successive images have been combined to improve statistics. Thus, we have ~ 240000 points to construct the distributions.

The typical examples of the PDF $P(\delta I,s)$ as a function of intensity variation δI for several spatial scales s are shown in Figure 2. The insets in Figure 2 illustrate the scale dependence of the maximum value $P(0,s)$ of the PDFs.

One can see that for the interval without aurora (Figure 2a) the PDF were practically independent on the scale s. There is only a small change of the shape of the central part ('core') of the PDF at $|\delta I|<8$ with an increase of the scale from 3 to 72 km. This leads to some decrease of the PDF maximum $P(0,s)$. The PDF for the smallest scale s=1.5 km noticeably differs from the PDFs for other scales. The possible reason of this is an interference between the value of intensity in neighboring pixels due to finite bandwidth of TV signal registration. Therefore in the stationary night sky a bright star occupies more than one pixel. (Another possible reason with the same result is a motion of aurora with velocity more than ~1.5 km/s, but this is not a case.)

When the aurora appears in the TV ASC field of view, we can see a deviation of the PDF of intensity fluctuations from the simple form characterizing the night sky. It is seen that these PDFs have a clearly non-Gaussian leptokurtic shape (Figure 2b-d) which means that the fluctuations of the auroral intensity are strongly intermittent. Another remarkable feature of the PDFs is a strong dependence on the spatial scale. Typically the PDFs are wider for a larger spatial scale.

4. Scaling features of GSF

The spatial generalized structure function (GSF) at a given time is defined for our problem as $S_m(s) = \langle|\delta I(p, s)|^m\rangle$, where $\delta I(p,s) = I(p+s) - I(p)$, and the angle brackets imply averaging over position p. To avoid the influence of the rare extreme fluctuations, resulting in statistically meaningless tails of the distribution, *Hnat et al.*, (2003) suggest the conditioning technique (*Kovács et al.*, 2001). Under the conditioning, the GSF for our case can be expressed via the PDF of the fluctuations as:

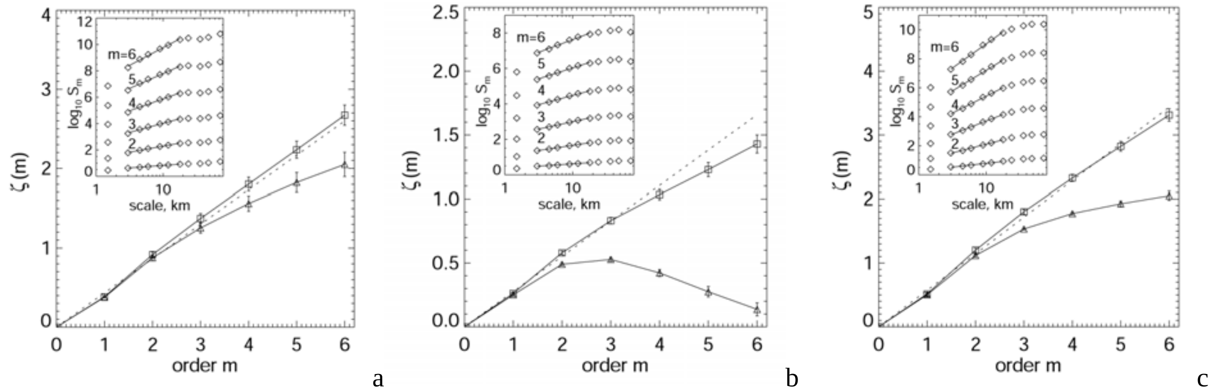
$$S_m(s) = \int_{-A}^{A} |\delta I|^m P(\delta I, s)\, d(\delta I)$$

Here the choice of the threshold A is based on the standard deviation of the intensity fluctuations on the given scale s, $A(s) = C\,\sigma(s)$. In our consideration we adopted C=10. Also we considered a non-conditioned GSF using all available points.

If the GSF (conditioned or non-conditioned) exhibit scaling with respect to scale s, then $S_m(s) \propto s^{\zeta(m)}$. This appears to be the case for auroral fluctuations being examined. The examples for the cases 'b', 'c' and 'd' discussed in the previous section are presented in Figure 3.

From the inset plots in the figure (non-conditioned cases are not shown) one can see that the structure functions of the considered orders exhibit a well-defined power-law form in the range from 3 km to 20 km, so it is possible to estimate the scaling exponents $\zeta(m)$. If they were $\zeta(m) = \alpha\, m$ with α being constant, then the fluctuations would statistically be self-similar with a single scaling exponent α. The power-law exponents $\zeta(m)$ for the non-conditioned GSF, being plotted as a function of the moment order (see triangles in Figure 3), exhibit a clearly nonlinear relationship on m indicating the presence of multifractal intermittency in the signal (*Frisch*, 1995).

The conditioning technique extract mainly non-intermittent part of the signal. Therefore the power-law exponents $\zeta(m)$ for the conditioned GSF exhibit a nearly linear relationship on m as seen in Figures 3a,c. However in the case of Figure 3b the $\zeta(m)$ for higher orders (m>3) deviate considerably from linear relationship. Thus, we conclude that for this case the intermittent structure are not fully suppressed by the conditioning with $A = 10\ \sigma$.



a b c

Figure 3. Exponents of the conditioned (squares) and non-conditioned (triangles) generalized structure function as a function of order m for auroral intensity fluctuation in 20-s interval starting from: a - 22:26:20; b - 23:54:20; c - 00:10:20. Insets: the conditioned structure function S_m of orders m=1-6; solid lines are the least square power law approximation.

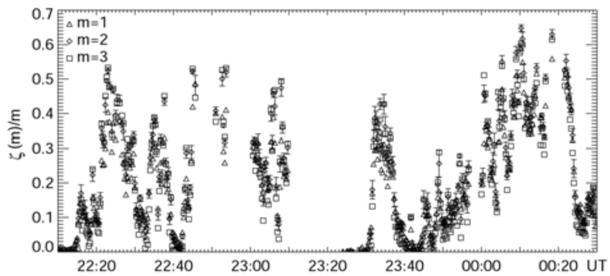


Figure 4. Evolution of the normalized scaling exponent of the conditioned GSF for orders m=1-3 during the considered event.

Having a few hours of observation in the course of the event considered it is possible to follow the temporal evolution of the scaling exponents. The temporal evolution of the normalized exponents $\zeta(m)/m$ for m=1,2,3 is presented in Figure 4. The values were calculated by the least square power law approximation of the conditioned GSF in the region of scales s=3-20 km for each 20-second interval of the data. We exclude from the consideration the intervals for which: i) TVASC range of gray levels does not cover the intensity range of aurora; ii) the standard deviation of intensity fluctuation $\sigma(s)$ > 25 for scales s <20 km (as we use the conditioning parameter A=10 σ and total number of the intensity levels is 256).

It appears that the normalized exponents $\zeta(m)/m$ for m=1,2,3 differs significantly from values <0.1 for the time period when no aurora appear in the field of view, to ~0.6 for the most disturbed periods. The value $\zeta(2)/2$ is the Hurst exponent, therefore the small values may be interpreted as anti-persistent fluctuations in the noise. However, as it was seen from PDF analysis, the source of the increase of the values is not a transformation to persistent fluctuations, but heavy tails in the fluctuation PDFs during aurora.

It is interesting that the values which the normalized exponent reaches during the development of each auroral activation are different and vary in region from 0.35 to 0.6. We should note that the values are not equal to theoretical values known for turbulent flows described by Kolmogorov's (1/3) or Kraihnan's (1/4) theories.

5. Discussion and conclusions

As we note in introduction, we especially consider the same data set of optical observations, that was previously used in (Kozelov et al., 2004). In that paper the data set was analyzed by spatio-temporal technique of selection of avalanche-like transients and it was founded that statistical distributions of the characteristics of these transients strongly supported the idea about the existence of SOC state in the magnetosphere-ionosphere plasma. Now, using the information about spatial distribution of the auroral luminosity we directly analyze the statistics of its spatial fluctuations: PDF at scales from ~1.5 to ~80 km and generalized structure function up to 6 order. We demonstrate that the data set share some scaling features which usually characterize the classical turbulence (Frisch, 1995). Unfortunately, we do not know any obvious theoretical relation between SOC and turbulence theoretical techniques. We can only note the scenario proposed by Chang et al. (2004) that induces an intermittent turbulence by a dynamical topological complexity which results from the nonlinear evolution of multiscale coherent structures. The observed scaling features are in a good agreement with this scenario.

The strong noise of the TV data registration complicate considerably the interpretation of the results. The noise also contains income from the airglow and the stars. The noise affected the most small intensity fluctuations and, therefore, for the 'core' of the PDF (δI<8) and for the GSFs of orders m<2. However, the noise fluctuations are shown to be practically independent on the spatial scales $s\geq 3$ km. So, the main source of the obtained spatial scaling is the auroral structures. By the same reason, the most informative for aurora are the

PDF's tails. In presence of aurora, the PDF's tails have a clearly 'heavy', non-Gaussian shape.

We have found that the GSFs of the considered orders *m*=1-6 vs spatial scale have a power law region at scales s=3-20 km. The power exponent ζ for the non-conditioned GSF has a non-linear dependence on GSF order, *m*, that for turbulent flows is usually interpreted as a manifestation of intermittent turbulence. For GSF conditioned with $A=10\sigma$ the dependence is mainly linear, but the non-linear dependence of ζ on *m* is sometimes seen for *m*>3. For the first three orders of GSF a deviation on linearity for $\zeta(m)$ is not large. So, we can conclude that the most part of the observed spatial structure is well described by one fractal dimension obtained as $\zeta(m)/m$ for *m*=2 or 3. We have found that these fractal dimension are varying in time during the event of interest. Changing of the fractal structure had been previously observed in simulation of Raleigh-Taylor instability (*Hasegawa et al*., 1996); the variations of fractal dimension of isoline of equal intensity had been previously obtained for aurora observations in (*Kozelov*, 2003). As we know, a theoretical description of such a transient in turbulent flows is an opened problem now.

The opened issue is also the relation between auroral structures and plasma disturbances in the magnetosphere. In spite of the fact that the main energy of the substrorm transient is located in the magneto-sphere plasma sheet, the source of the small scale structures is not well understood. There is no doubt, that the considered bright auroral structures are located at closed magnetic field. However, before the expansion phase of the discussed substorm, the quite aurora were located the south of the field of view. Therefore, we can assume that the observed poleward motion of the auroral structure really corresponded to a plasma transient in the magnetosphere plasma sheet (*Yahnin et al*., 2006). However the small scales of the structure are possibly affected by the acceleration region at the distances close to the Earth. The spatio-temporal technique (*Uritsky et al*., 2002; *Kozelov et al*., 2004) gives uniform scaling features of avalanche-like transients during substorm expansion phase from scales of a few square kilometers and a few seconds up to 10^6 kilometers and a few hours. The analysis of the PDFs and GSFs presented here shows that the feature (power-law region on GSF vs. scale, an evidence of intermittence, leptokurtic shape of the PDFs and collapse of the rescaled PDFs) of spatial auroral fluctuations on scales 3-20 km are the same as for non-substorm event discussed in (*Kozelov and Golovchanskaya*, 2006). Therefore the scaling relations are possibly a more common feature of dynamical systems than substorm-like transients in the magnetospheric plasma.

Acknowledgements. The study was partly supported by the Presidium of the Russian Academy of Sciences (RAS) through the basic research program "Solar activity and physical processes in the Sun-Earth system" and by the Division of Physical Sciences of RAS through the program “Plasma processes in the solar system”.

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