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DEVELOPMENT OF AURORAL INTENSIFICATION AS AN OUTPUT OF MAGNETOSPHERE-IONOSPHERE DYNAMICAL SYSTEM

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Abstract. Using TV data observations we analyse the development of different kinds of auroral intensifications. The set of TV images is considered as an output of magnetosphere-ionosphere dynamical system. To characterise the complexity of the auroral image we use the fractal dimension spectrum of equal intensity lines. From the spectrum the auroral form has been separated from background noise, and the most variable intensity level has been selected. A modification of Grassberger-Procacci method has been used for studying the low-dimensional dynamics of the magnetosphere-ionosphere system which generates the image set. Our consideration is mainly aimed at the difference between pseudo-breakups and major substorm onsets.

Introduction

To study the processes in the magnetosphere-ionosphere system by aurora phenomena it is necessary to separate temporary and space variations of optical data. The television techniques enable us to register auroral form with high temporary and space resolution. It is possible to mark temporary variations of auroral intensity by integration of a sequence of the TV images in an area, using virtual "photometers" or keograms. We can also investigate space distribution of auroral luminosity in each image. However the information about space dynamics of auroral phenomena is not used completely, though this information is most detailed for the whole magnetosphere-ionosphere system.

In this paper we consider the set of TV images as an output of magnetosphere-ionosphere dynamical system. To characterise the complexity of the auroral image we use the fractal dimension spectrum of equal intensity lines. The spectrum we use to reveal the auroral form from background noise and to select the most variable intensity level. The modification of Grassberger-Procacci method has been used for studying of the low-dimensional dynamics of the magnetosphere-ionosphere system which generates the image set.

Isoline dimension spectrum

To characterise the complexity of the auroral image we use the fractal dimension spectrum of equal intensity lines (Kozelov,1997,2000). The calculation procedure used is based on the box-counting method (Feder,1988) and includes the following steps:

1). The isoline of equal intensity $L(I)$ has been obtained for each level of intensity I in digitized TV image.

2). Using pixels as a mesh, the number $N(d,I)$ of boxes of side d (from d=1 to d=128) that overlap the isoline $L(I)$ have been counted.

3). The dimension $D(I)$ of isoline $L(I)$ is the logarithmic rate at which $N(d,I)$ increases as d decreases, and it has been estimated by the gradient of the graph of $\log N(d,I)$ against $-\log d$ for each I.

The box-counting dimension obtained in the calculation procedure is an estimation of fractal dimension (Falconer, 1995). However, the range of scales available in TV image is not large, therefore we only mean the pre-fractal structure, not the fractal one, which suggests a limit for $d \to 0$. In any case, the number of mesh boxes of side d that intersect an isoline is an indication of how spread out or irregular the line is when examined at scale d. The dimension reflects how rapidly the irregularities develop as d decreases. Theoretically the dimension of subset of plane may have a value in the range from 0 (dimension of disconnected set of points) to 2 (dimension of plane figures). Dimension of a smooth line is equal to 1.

Usually, when an auroral form is present in the image, there are three important regions on the $D(I)$ curve: 1) the region of noised background intensities; 2) the region of the most structured intensities (MSI); and 3) the region of separation between them. The MSI region corresponds to the most structured isolines in the auroral form, and the dimension value for the MSI is usually greater than 1.25. For the region of separation the dimension value is smaller and usually in this region there is an intensity with a minimum dimension. The isoline for this intensity separates the auroral form from the noise background. In the region of the noise background the dimension value increases while the intensity decreases.

What we can say about magnetospheric processes using the results of dimension calculations? An aurora is a manifestation of some magnetospheric processes, and it is supposed that auroral structure is connected with the structure of spatial region of these processes' action. The dimension may be used as a numerical characteristic of spatial irregularity of the region. The dimension of MSI on $D(I)$ curve would be connected with the main region of this irregularity. When we see the increase of this dimension, this may be a reason to talk about development of the irregularity. Therefore, we can suggest that the variation of MSI dimension expresses the dynamics of nonlinear dissipative system, which describes this irregularity development.

Grassberger-Procaccia (GP) algorithm

In general case, dynamics of nonlinear dissipative system are described by a trajectory in the phase space. Formally the system can have many degrees of freedom (parameters), however it was shown, that in many cases the behaviour of the dynamic systems basically depended on a small number of critical parameters. In other words the trajectory of a system in the phase space lies near the low-dimensional surface of attraction. If we assume, that a set of measurements is a section (projection) of this trajectory, it is possible to estimate the dimension of this trajectory, designing a multi-dimensional space by one-dimensional data set. Usually, the procedure consists in the following (Grassberger and Procaccia, 1983). From experimental temporary set $x(t)$, consisting of measured values, there will be formed d-dimensional vectors X_n, $n = 0, 1,...$, the coordinates of which consist of sub-sets x with consistently growing shifts, divisible into time of data quantization, i.e.

$$\boldsymbol{X}_i = \{x(t_i), x(t_i+t), \dots, x(t_i+(d\text{-}1)t)\} \qquad (1)$$

At rather a large shift the $\boldsymbol{X}_n$ vectors are independent, therefore they can be accepted for a sequence of points in d-dimensional phase space. For the choice of time of quantization it is recommended to choose its equal to 1/2 or 1/4 from time, at which the autocorrelation function of $x(t)$ reaches the first minimum.

The correlation integral is calculated on the constructed set of $\boldsymbol{X}_n$. The correlation integral determines the probability pays off that distance between a pair of vectors is less, than the given distance r:

$$C(r) = \frac{1}{N^2} \sum_{i=1}^{N} \sum_{\substack{j=1 \\ j \neq i}}^{N} \theta(r - |\mathbf{X}_i - \mathbf{X}_j|), \qquad (2)$$

where θ is Heaviside function, N is the number of vectors in the set. If the correlation integral depends on r under the power law $C(r) \sim r^b$, the parameter of a degree represents the correlation dimension of the process $b=D_c$. This dimension is an estimation from below for Hausdorf dimension D: $D_c \leq D$. Practically, for determination D_c it is necessary to construct the dependence $log\ C\ (r)$ from $log\ r$ at various growing dimensions of the embedding space. The calculation is finished, if the inclination of the diagram does not vary already with the increase of d. It is possible to consider the estimated value of D_c rather reliable, if it does not vary down to $d=2D_c + 1$.

The described method is usually applied for the estimation of correlation dimension at $D_c < 10$, and it is used as an evidence for the benefit of the fact that the behaviour of the system is described by a small number of differential equations. If the obtained value of D_c is not an integer, then one usually say, that the system has fractal (strange) attractor. In case of white noise at any value of d the saturation of correlation integral does not occur and $C(r) \sim r^b$. If at experimental data set there is a noise with amplitude r_0, then for scales $r<2r_0$ the behaviour of correlation integral corresponds to the expression for white noise. However for scales $r>2r_0$ the presence of noise does not influence the behaviour of correlation integral. This property permits to separate chaotic process of the dynamical origin from additive white noise.

GP-algorithm application to TV data processing

We chose three cases of TV auroral observation when the auroral intensifications were in the zenith:

1) February 8, 1997, from 19:18 UT, Lovozero;
2) March 1, 1997, from 18:48 UT, Lovozero;
3) January 11, 1997, from 20:08 UT, Porojarvi.

We consider the sequence of TV images as an experimental data set. However, for the application of GP-algorithm for calculation of correlation integral (2) it is necessary to define the distance between vector components. In this case each component is a TV image. In other words, it is necessary to define "distance" between TV images. Here we offer the following method of introduction of distance (metre) in space of TV images (Kozelov and Vjalkova, 2001).

For an auroral structure, dynamics of which is necessary to investigate by isoline dimension spectrum we select the level of intensity, on which this structure is conspicuous. In all images we assign a value equal to 0 to the pixels with values less than the given level. We assign to other pixels the value equal to 1. After this we consider the distance between two images to be simply a number of pixels, having different values in these images.

The distance entered in such way has all properties of a metric one and in this sense is correct. For the calculation of correlation integral by (2) we used the suprenum-norm for vectors in embedding space.

The isoline dimension spectrum $D(I)$ as a function of time for each case is presented in Fig.1. The moments of breakups (BU) and pseudo-breakups (PBU) determined by usual morphological features are marked.

Correlation integrals calculated by GP method for the marked intensity levels in Fig.1 are presented in Fig.2. The region of power law dependence in each plot is marked by the dashed line. For these regions the dependences of the slot (power) on the dimension of embedding space are presented in Fig.3. The relative spatial scale of self-similarity (obtained by boundaries of power law regions in Fig.2) is shown in Fig.4 for the three discussed cases of auroral intensifications.

Conclusions

1) Usually after pseudo-breakups the MSI (Most Structured Intensities) on $D(I,t)$ plate are localized in a small range of intensities. After the substorm onset the MSI are varied in full intensity range.

2) There is no clear boundary between pseudo-breakups (cases 2 and 3) and simple brightening of the auroral arc (case 1).

3) Correlation dimensions for pseudo-breakup and breakup intensifications are the same (~2.7-2.8). This dimension differ from the one obtained in (Kozelov and Vjalkova, 2001) for pulsing patches (~2 for one patch and ~7 for full image).

4) There is a difference between the pseudo-breakup and breakup intensifications: the linear region on $C(r)$ plot (see Fig.2) is shorter for pseudo-breakup. This difference means that the spatial scale of pseudo-breakup is smaller than for the breakup (Fig.4). This conclusion is consistent with the results of other observations (Koskinen et al., 1993; Nakamura et al., 1994; Pulkkinen et al.,1998): PBUs are small activations observed in the magnetosphere and in the ionosphere, but PBU do not lead to the global reconfiguration of the magnetosphere that is observed during large scale substorm (BU).

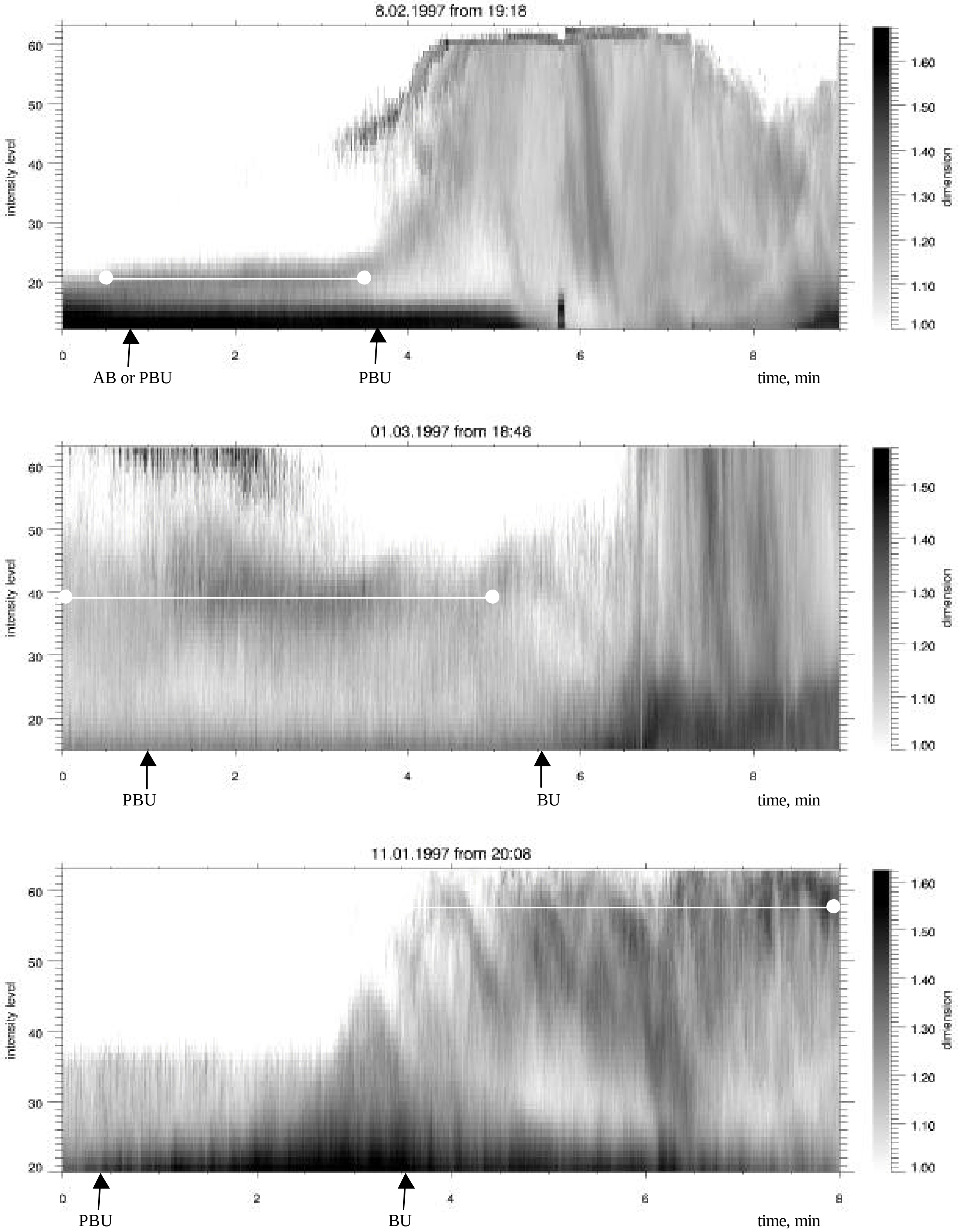

Fig.1. Isoline dimension spectra for three cases of TV observations. The moments of arc brightening (AB), breakups (BU) and pseudo-breakups (PBU) are marked by arrows. The sets of images and intensity levels used in GP algorithm are marked by white lines.

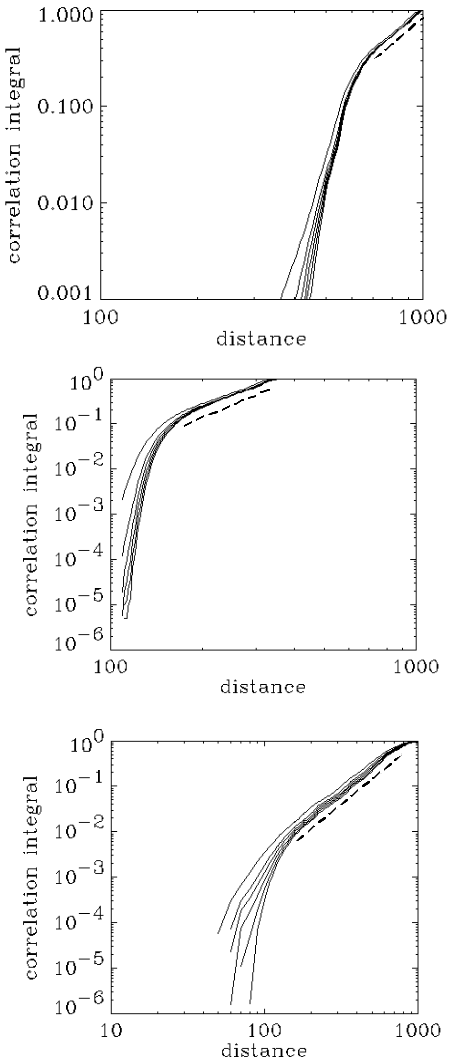

Fig.2. Correlation integral as a function of distance calculated at dimensions of embedding space d = 2, 6, 9, 12, 15, 18. Dashed lines are the regions of power law dependence.

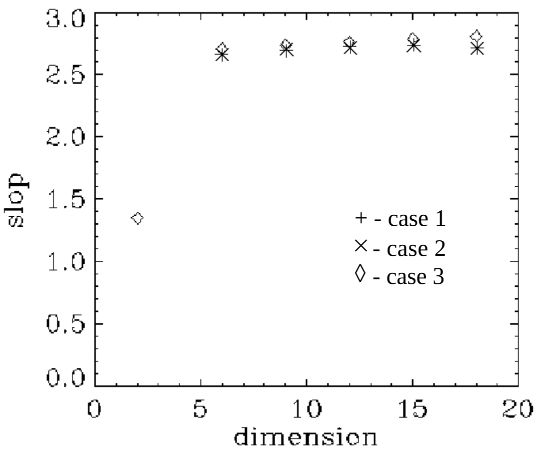

Fig.3. Dependences of the slot on dimension of embedding space.

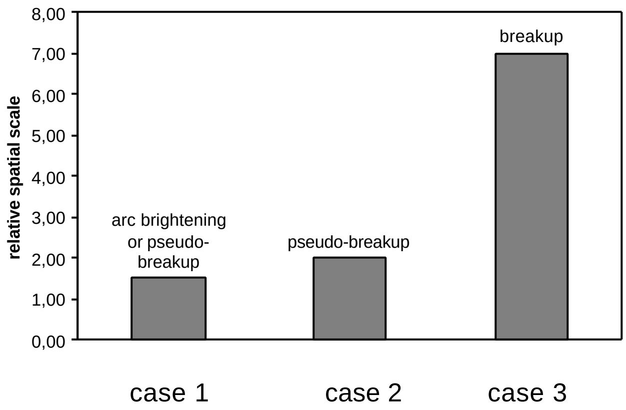

Fig.4. Comparison of the spatial scale of self-similarity for the observed auroral intensifications.

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References

Falconer, K.J., *Fractal Geometry: Mathematical Foundations and Applications.*, John Wiley & Sons, New York, 1995.

Feder, J., *Fractals*, Plenum Press, New York, 1988.

Grassberger, P., and Procaccia, I., Characterization of strange attractors, *Phys.Rev.Let*., *50*, #5, 346-349, 1983.

Koskinen, H. E. L, Lopez, R. E., Pulkkinen, R. I., Baker, D. N., and Bosinger, T., Pseudo-breakup and substorm growth phase in the ionosphere and magnetosphere, *J. Geophys. Res.*, *98*, 5901, 1993.

Kozelov, B.V., Application of methods of fractal analysis to data of ground based observations, *in Equipment and Methods of Geophysical Measurements*, edited by V.E.Ivanov, Kola Science Center RAS, Murmansk, 107-118, 1997.

Kozelov, B.V., Fractal characteristics of spatial structure of aurora, *in: Phisics of the near-earth space*, Kola Science Centre RAS, Apatity, 572-596, 2000.

Kozelov, B.V., and Vjalkova, N.Y.**,** Search of temporal chaos in TV images of aurora, *Int. J. Geomagnetizm and Aeronomy* (accepted), 2001.

Nakamura, R., Baker, D. N., Yamamoto, T., et al., Particle and field signatures during pseudobreakup and major expansion onset, *J. Geophys. Res*., *99*, 207, 1994.

Pulkkinen, T.I., Baker, D.N., Frank, L.A., et al., Two substorm intensifications compared: Onset, expansion and global consequences, *J. Geophys. Res.*, *103*, 15-27, 1998.