Пространственно-временные структуры в овале полярных сияний: подходы к моделированию

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Содержание

- Переходные процессы в магнитосферно-ионосферной (МИ) системе
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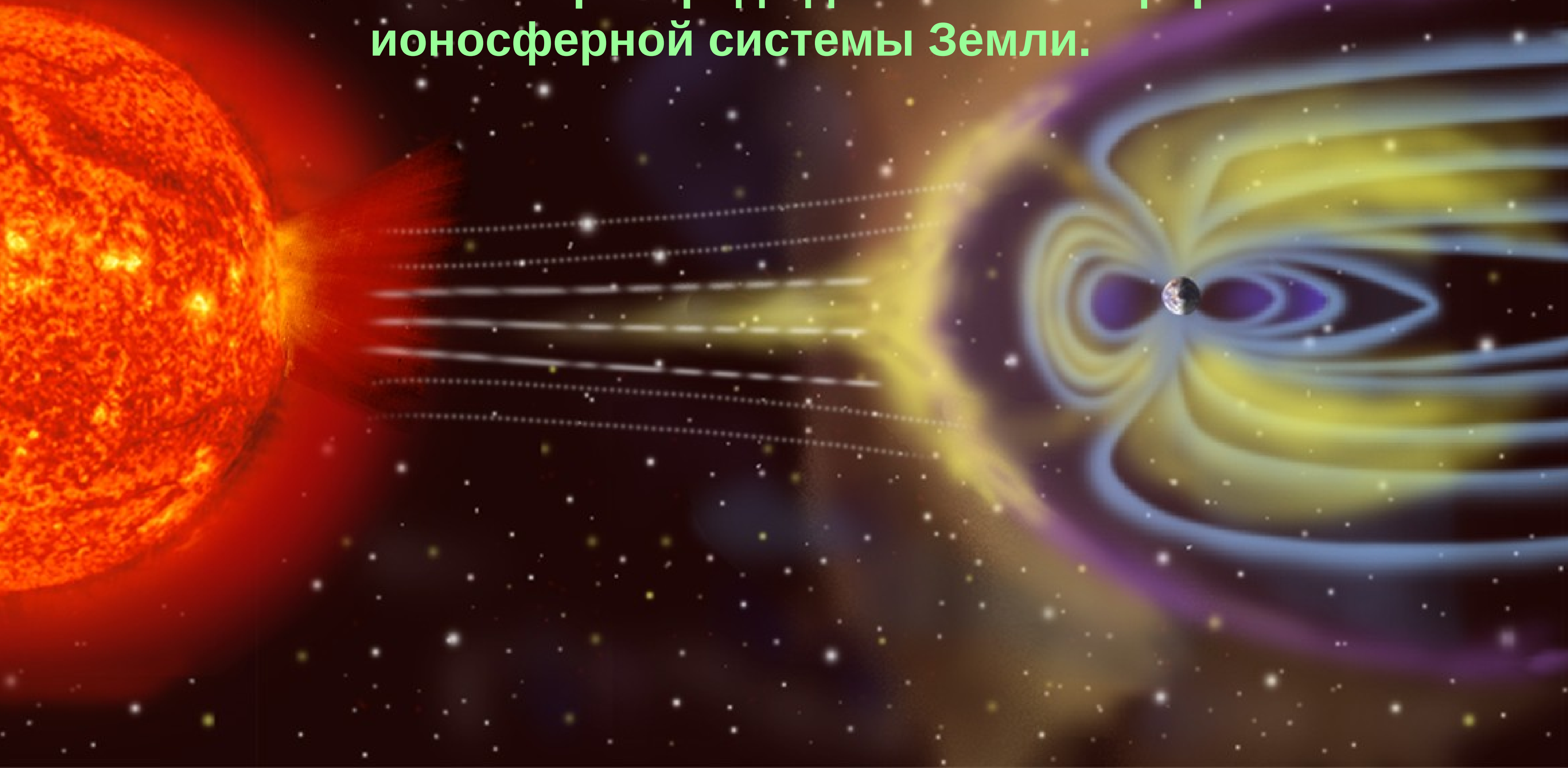
- Самоорганизованная критичность или турбулентность
- Структура авроральных возмущений и процессы в магнитосферно-ионосферной плазме
- Геометрия фракталов и мультифракталов

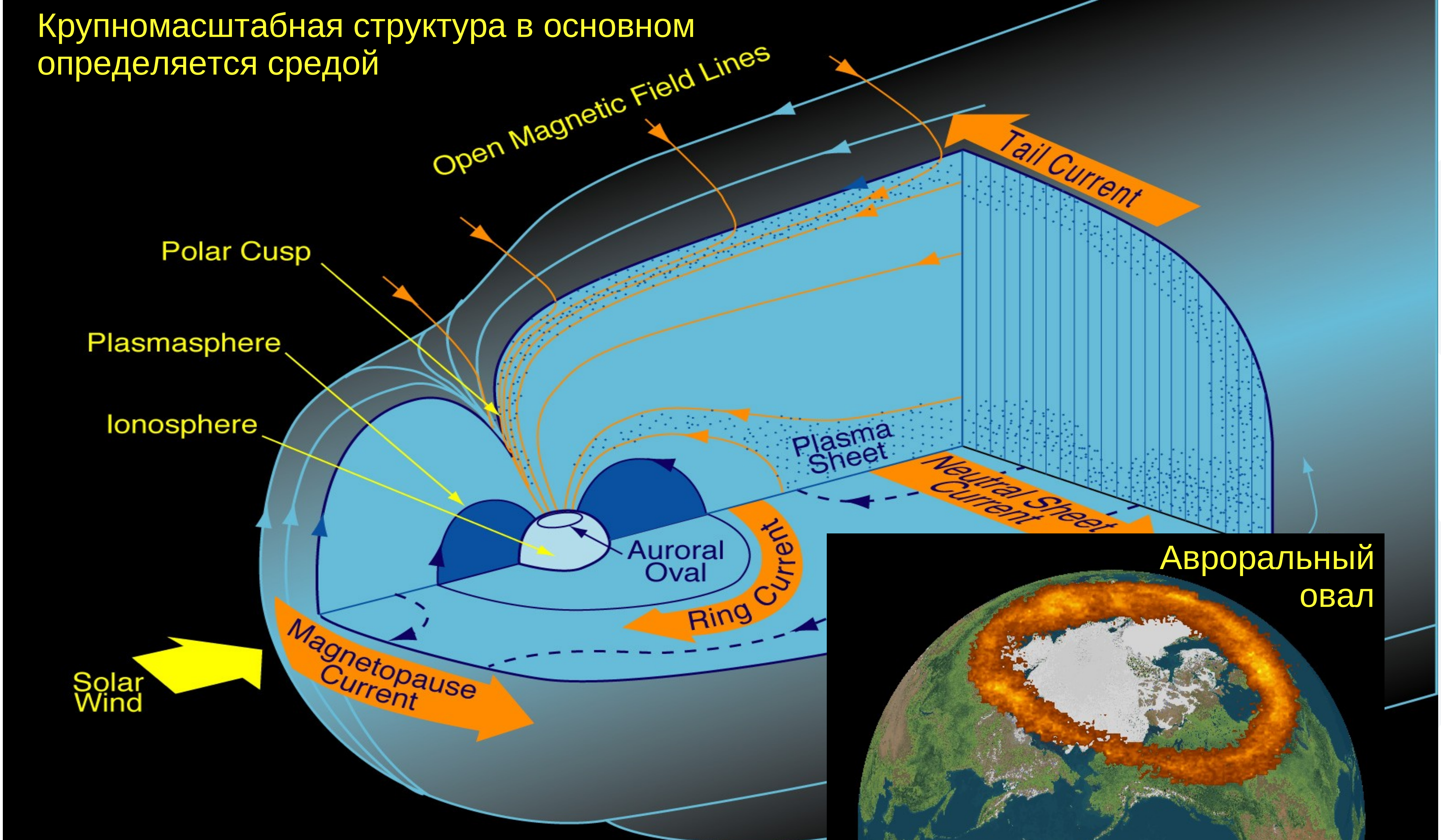
В докладе обсуждаются подходы к разработке модели пространственно-временной структуры аврорального овала, основанные на фрактальных и мультифрактальных характеристиках.

Работа поддержана грантом РНФ № 22-12-20017 «Пространственно-временные структуры в околоземном космическом пространстве Арктики: от полярных сияний через особенности самоорганизации плазмы к прохождению радиоволн».

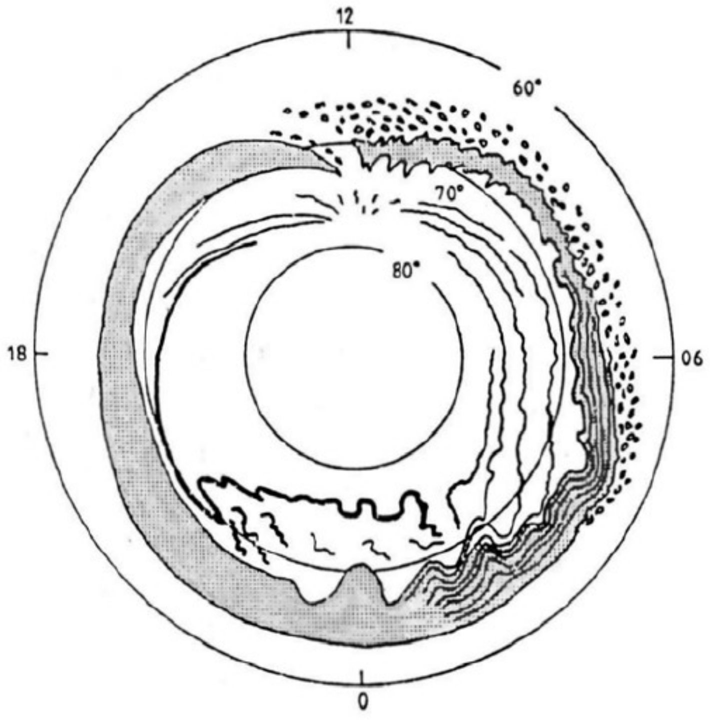
Солнце является основным источником энергии и частиц. Солнечный ветер – среда для магнитосферно-ионосферной системы Земли.



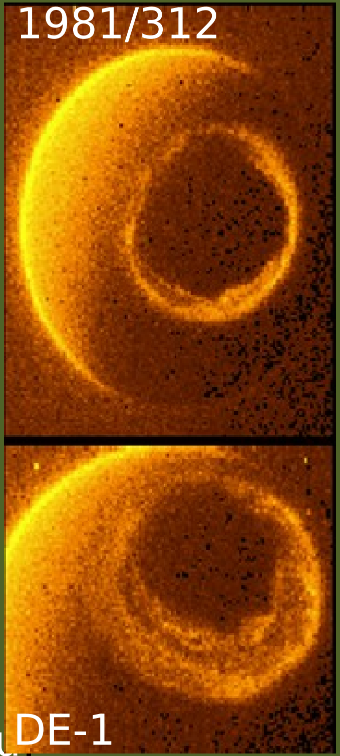
Крупномасштабная структура в основном определяется средой



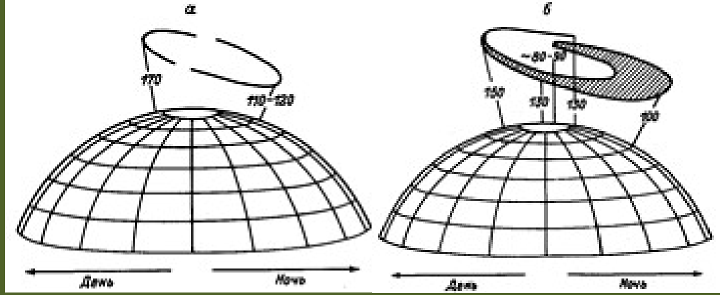
Auroral forms within the oval



Schematic figure of aurora by S.-I. Akasofu



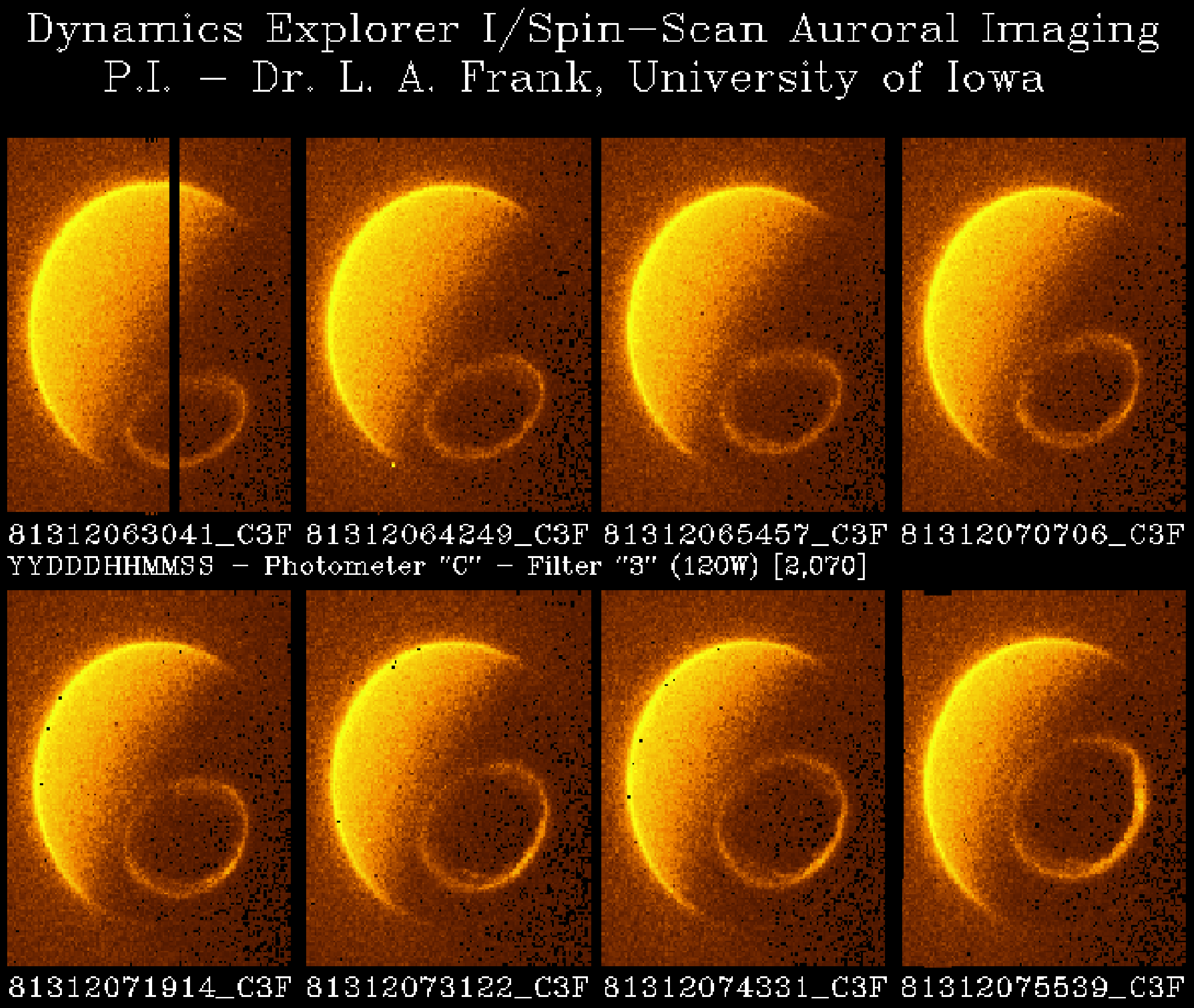
DE-1
[L.A.Frank]



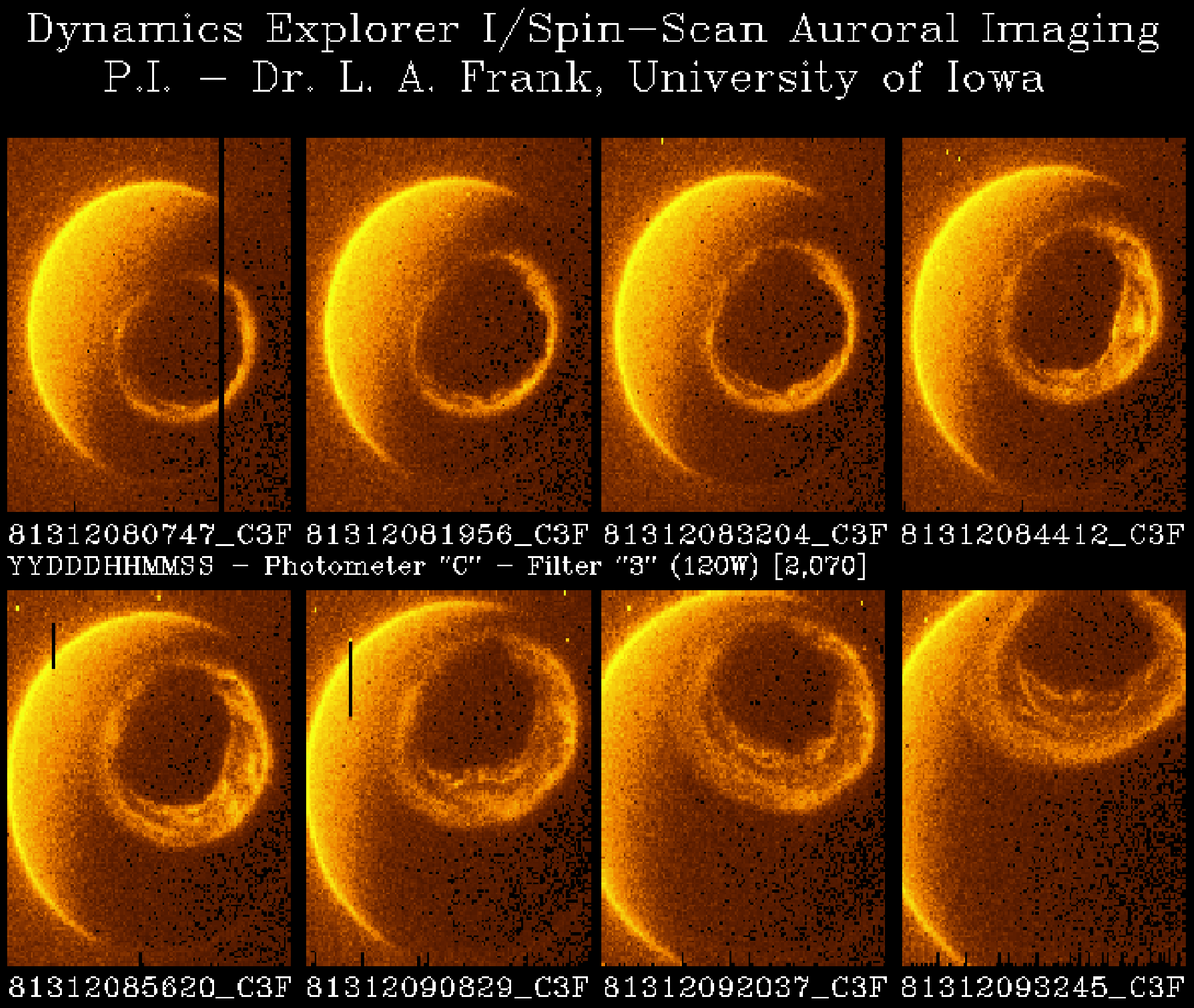
During the International Geophysical Year (IGY) (1957-58), space scientists all around the world coordinated their efforts to record the aurora from many places at the same time. From the analysis of this data, two important concepts in auroral physics were born: "auroral oval" [Feldstein and Starkov]and "auroral

- Diffuse aurora equatorward of the main oval.
- Discrete auroral arcs
- Homogenous bands
- Curtains or draperies
- Rayed arcs
- Folds and curls
- North-south auroral arcs (streamers)
- Polar cap arcs (theta aurora)
- Omega bands
- Westward travelling surge and auroral bulge
- Auroral patches
- Pulsating or flickering

Спокойный авроральный овал

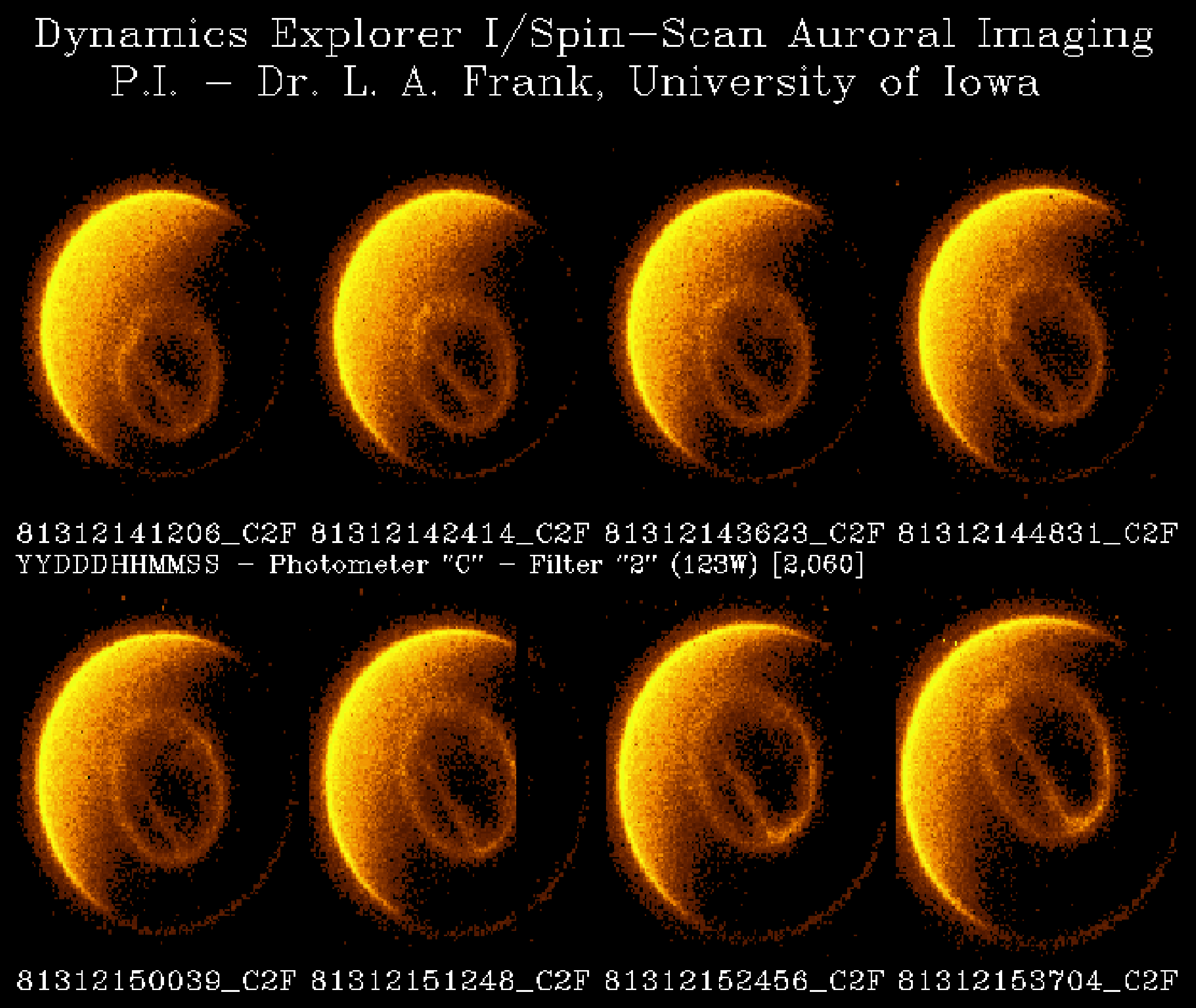


Авроральный овал во время суббури



Тета- аврора

Bz>0

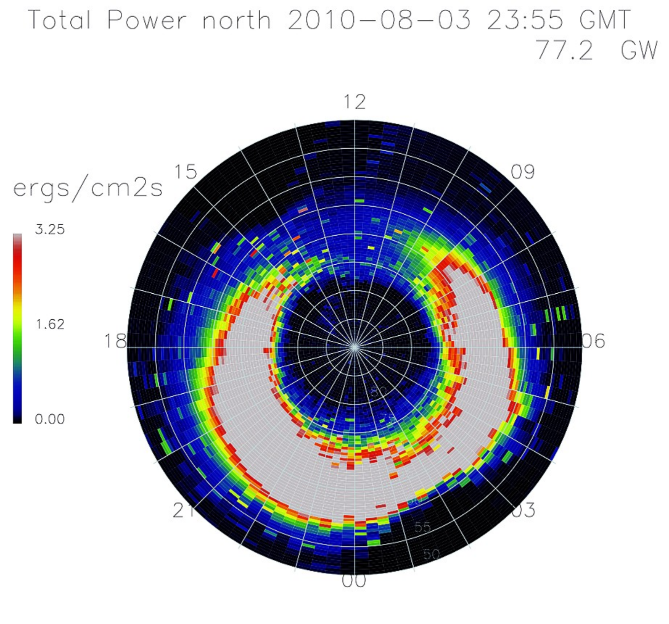


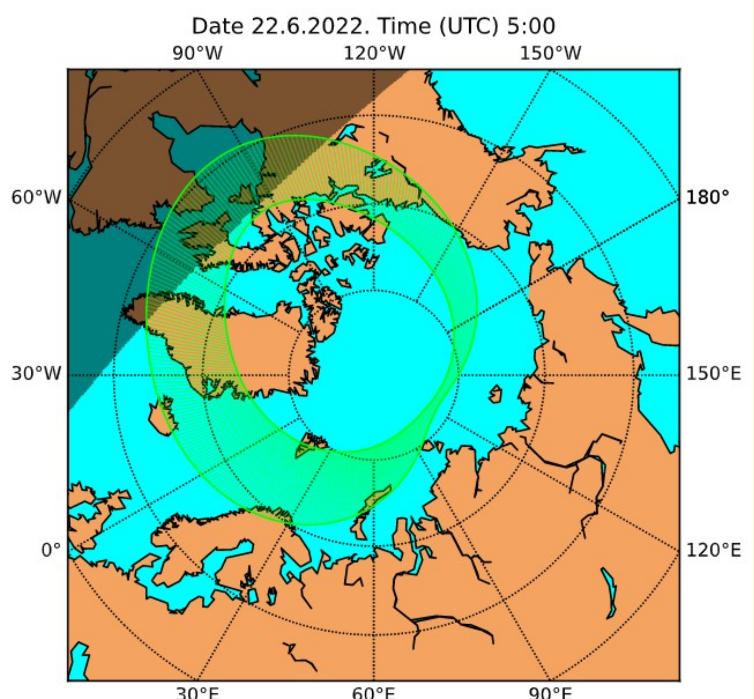
Модели овала

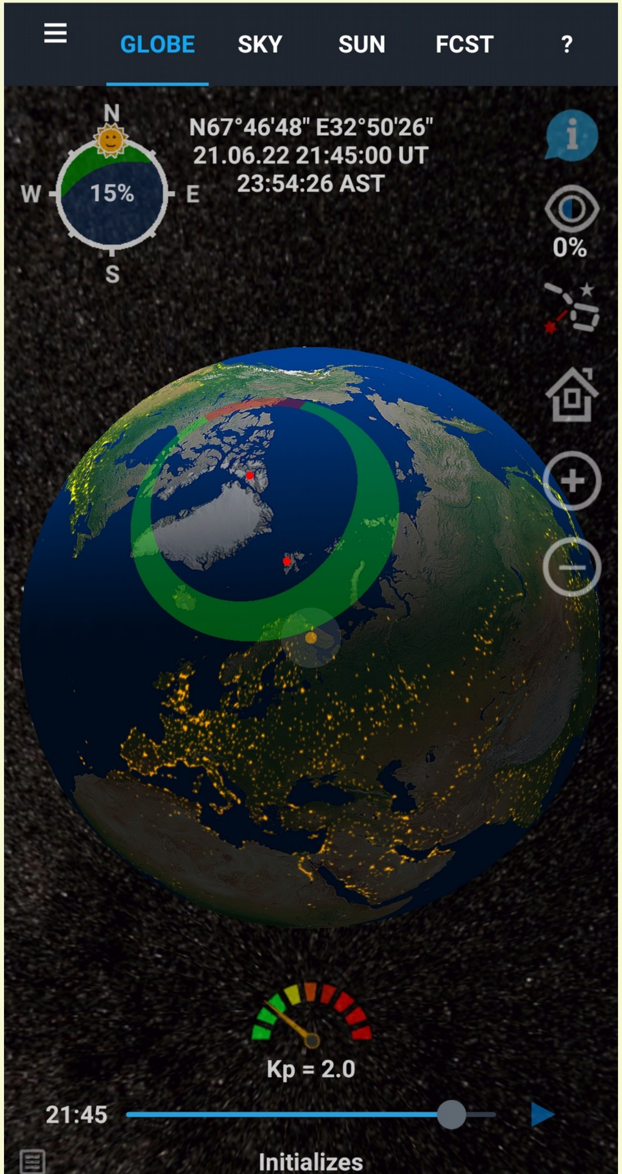
Старков-Фельдштейн
OVATION-Prime

Kp-index

Границы и основные потоки, без структуры





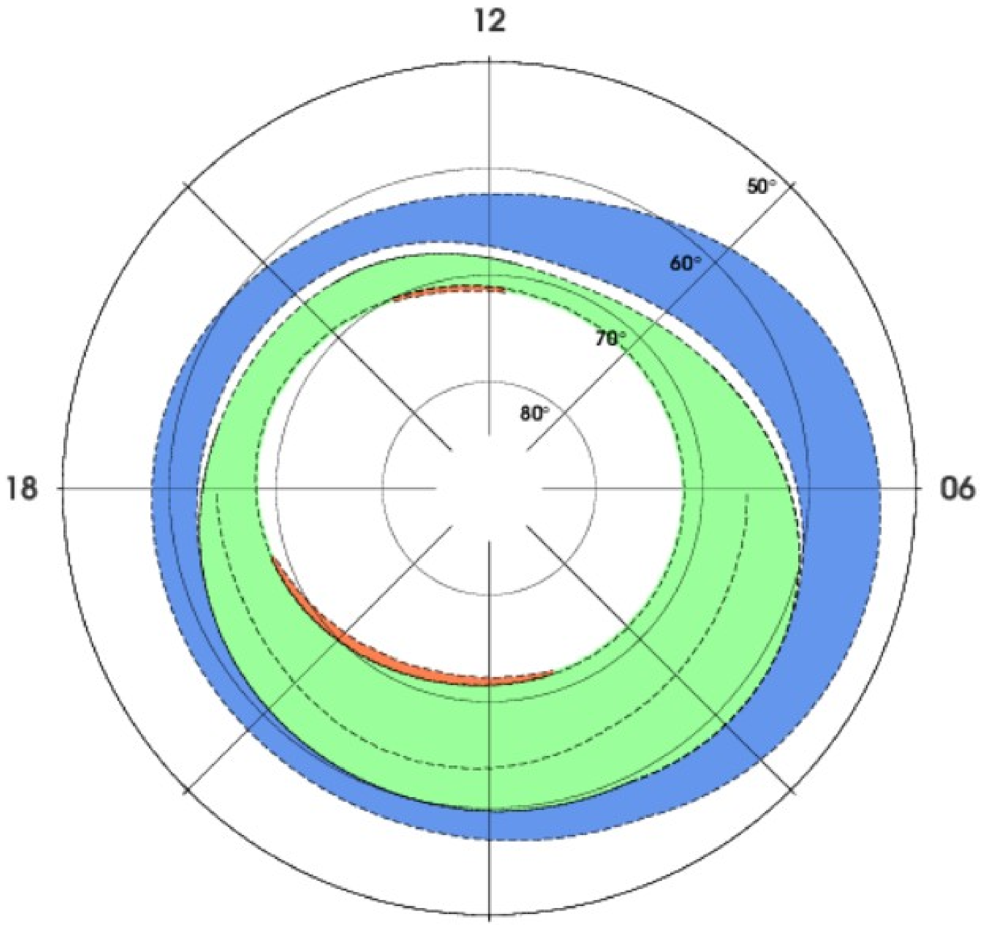


Auroral precipitation model

The model presented here shows the planetary distribution (corrected geomagnetic latitude - local geomagnetic time) of different type auroral precipitation (location, average energy and energy flux) depending on a level of the geomagnetic activity determined by AL and Dst indexes.

Vorobjev V.G., Yagodkina O.I. Effect of magnetic activity on the global distribution of auroral precipitation zone // Geomagnetism and Aeronomy. V. 45. № 4. P. 438-444. 2005.
Vorobjev V.G., Yagodkina O.I. Auroral precipitation dynamics during strong magnetic storms // Geomagnetism and Aeronomy. V. 47. № 2. P. 185-192. 2007.

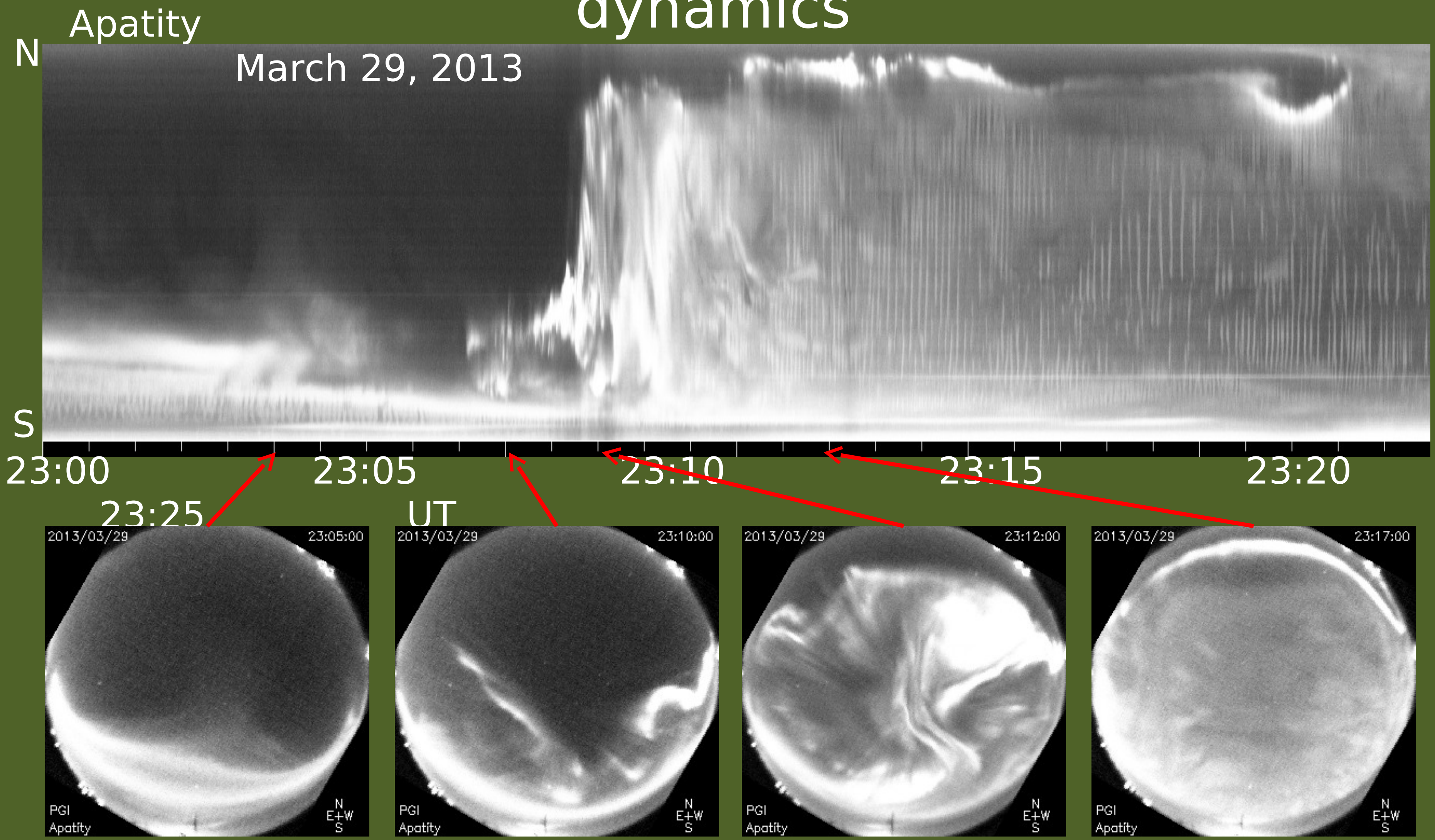
http://apm.pgia.ru/



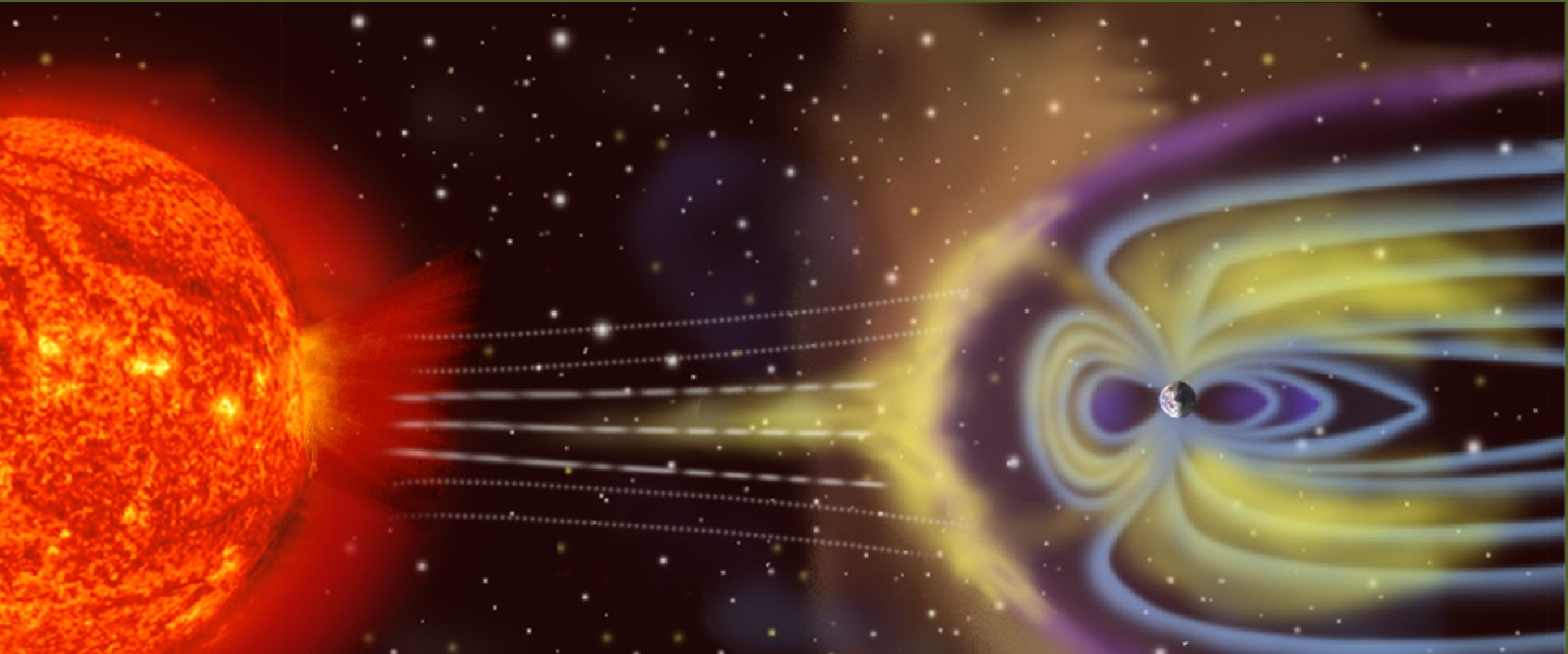
AURORAL PRECIPITATION MODEL (ZONES)
MODEL INPUTS:
AL = −500nT
DST = −100nT

generated by PGI Auroral Precipitation Model (http://webapps.pgia.ru/apm/)

Keograms (N-S cross sections) – latitudinal dynamics



Aurora is a result of plasma processes in system Sun-Solar wind-Magnetosphere-Ionosphere



The complex system approach

The Earth's magnetosphere-ionosphere system is a complex non-linear system, far from equilibrium state, but the external forcing by solar wind lead it to neighboring of self-organized critical (SOC) state.

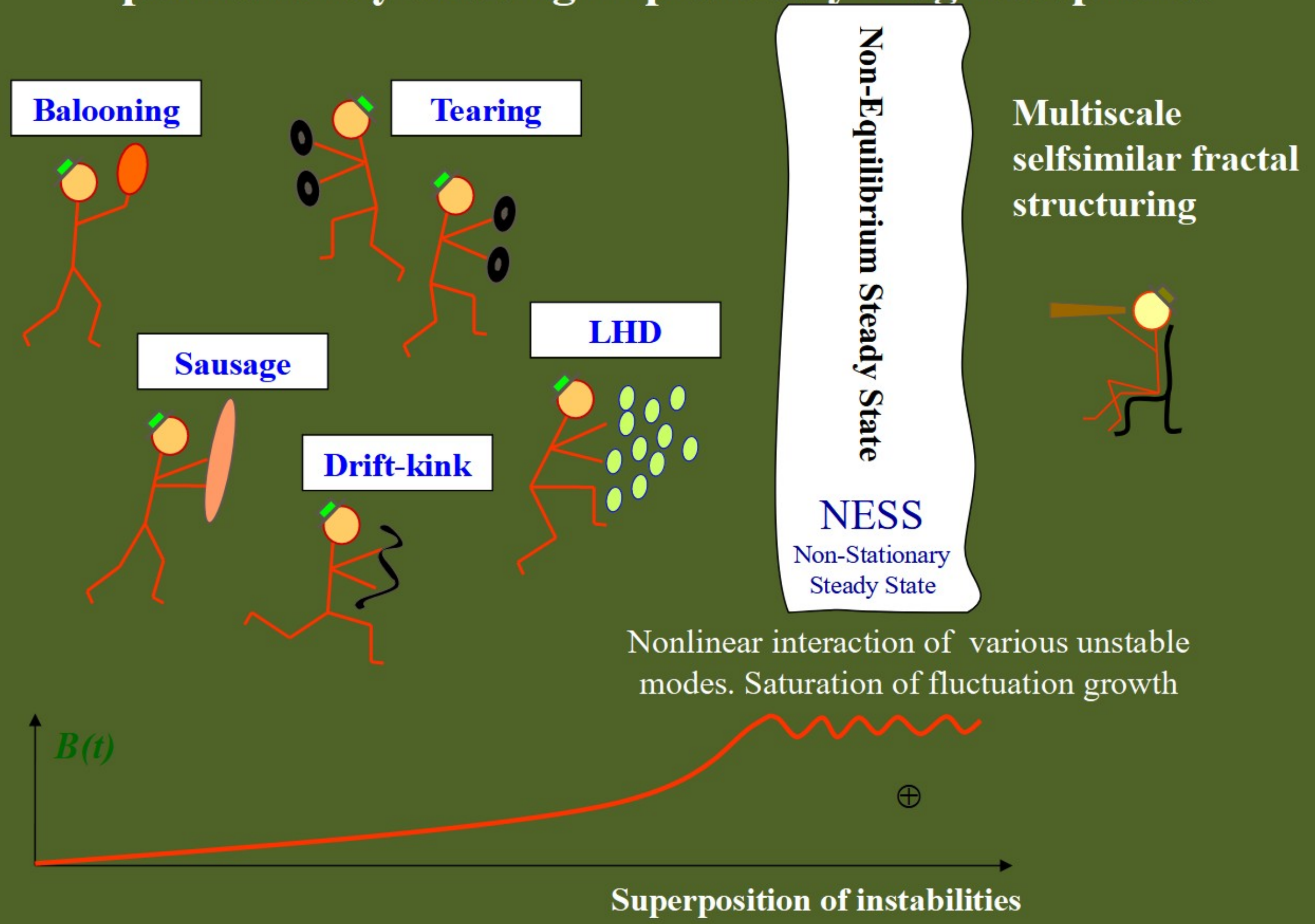
Unlike to a linear system, the non-linear system should be studied by dynamics of transients.

Substorms… !

The breakup gives us a unique possibility to see the auroral response to the turbulent magnetospheric fields applied to the ionosphere.

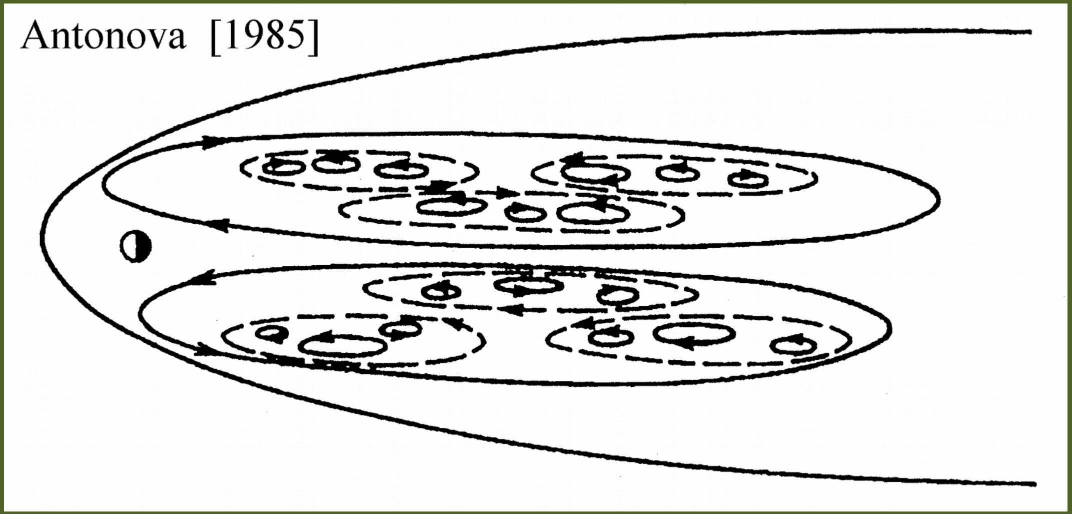
The aim of data analysis: to consider the scaling features of spatial fluctuations in auroral luminosity and its time evolution at the early breakup stage.

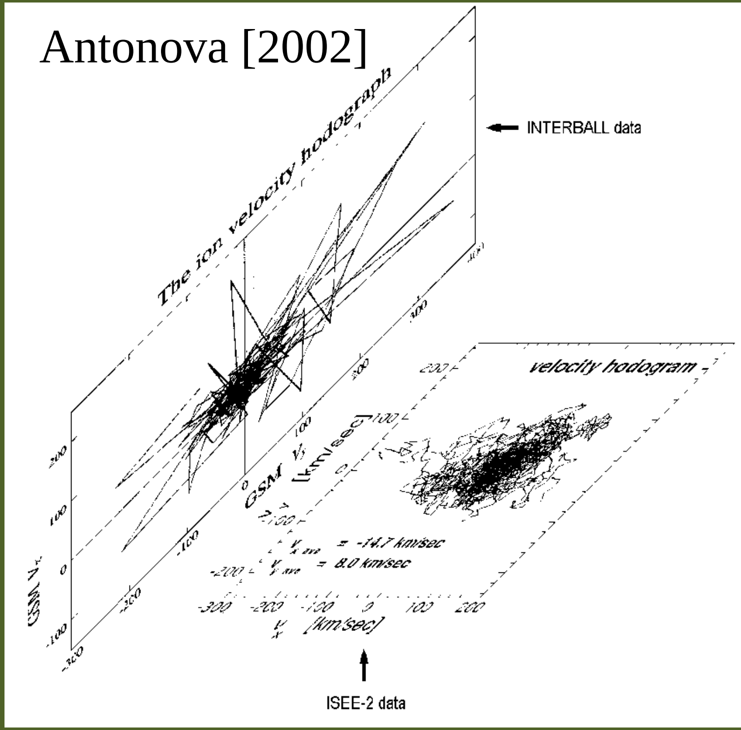
Magnetotail – open, extremely dynamic system (β≥1), permanently existing in planetary magnetospheres

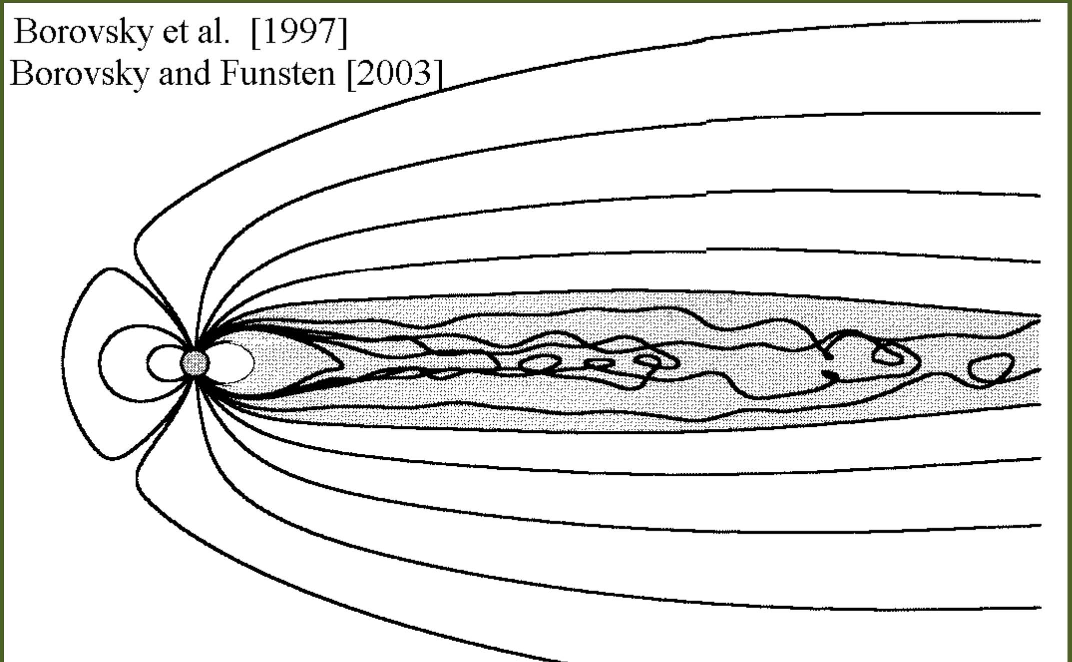


[Milovanov A. and Zelenyi L.,]

Turbulent dynamics of magnetosphere plasma







Self-organized critical (SOC) state

- Spatiotemporal evolution of transients follows distinct power-law statistical relations, including power-law scaling of occurrence probabilities of the duration, area, energy output and some other relevant quantities.
- These scaling laws strongly suggests the existence of a universal dynamical principle, such as self-organized criticality (SOC) , arranging the system dynamics in a uniform scale-free fashion across quite different spatial and temporal scales.
- More details about self-organized criticality, avalanche analogy and sandpile models see in [Bak, 1997; Jensen, 1998]

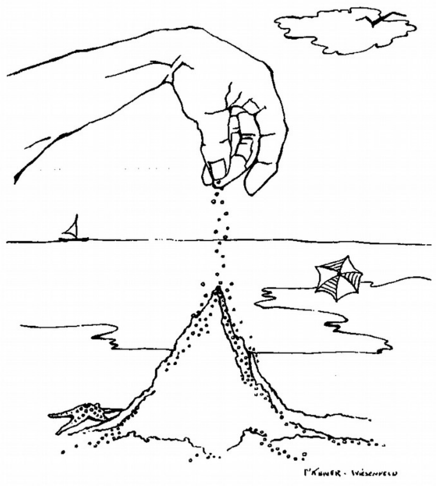
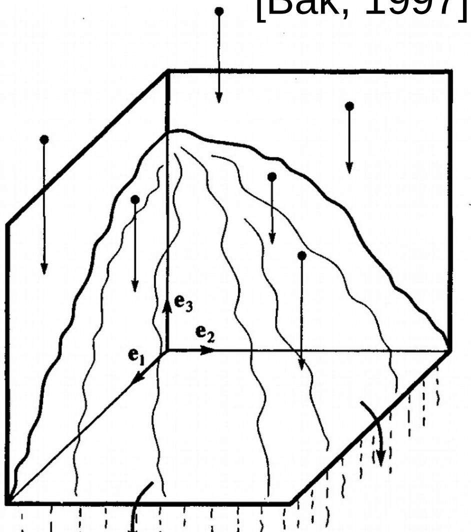


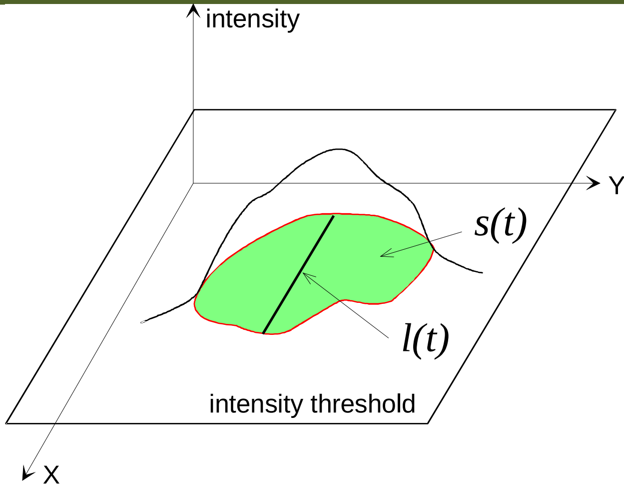
Figure 1. Sandpile. (Drawing by Ms. Elaine Wiesenfeld.)

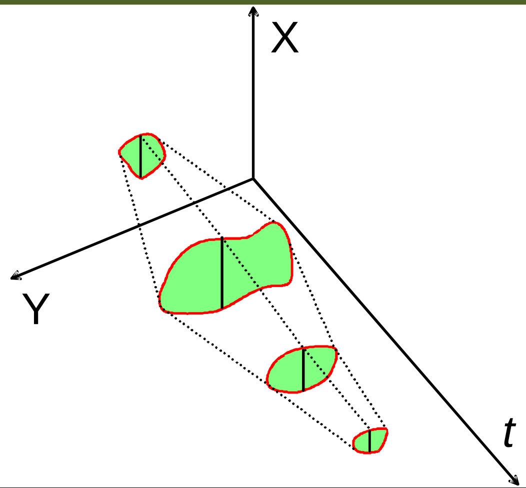
[Bak, 1997]

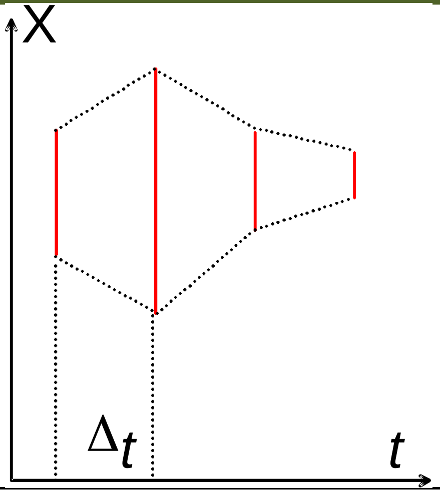


[Jensen, 1998]

Avalanche analysis:
1-D and 2-D characteristics of auroral spots







Characteristics	2-D spatial spots	1-D spatial spots
Integrated size	$S = \int_{\{T\}} s(t)dt$	$L = \int_{\{T\}} l(t)dt$
Total dissipated energy	$E = \int_{\{T\}} w(t)dt$	$E = \int_{\{T\}} w_l(t)dt$
Maximum spatial size	$A = \max_{\{T\}} s(t)dt$	$L_{\max} = \max_{\{T\}} l(t)dt$
Maximum dissipated power	$W = \max_{\{T\}} w(t)dt$	$W = \max_{\{T\}} w_l(t)dt$

Optical observations during 19-20 January 2001

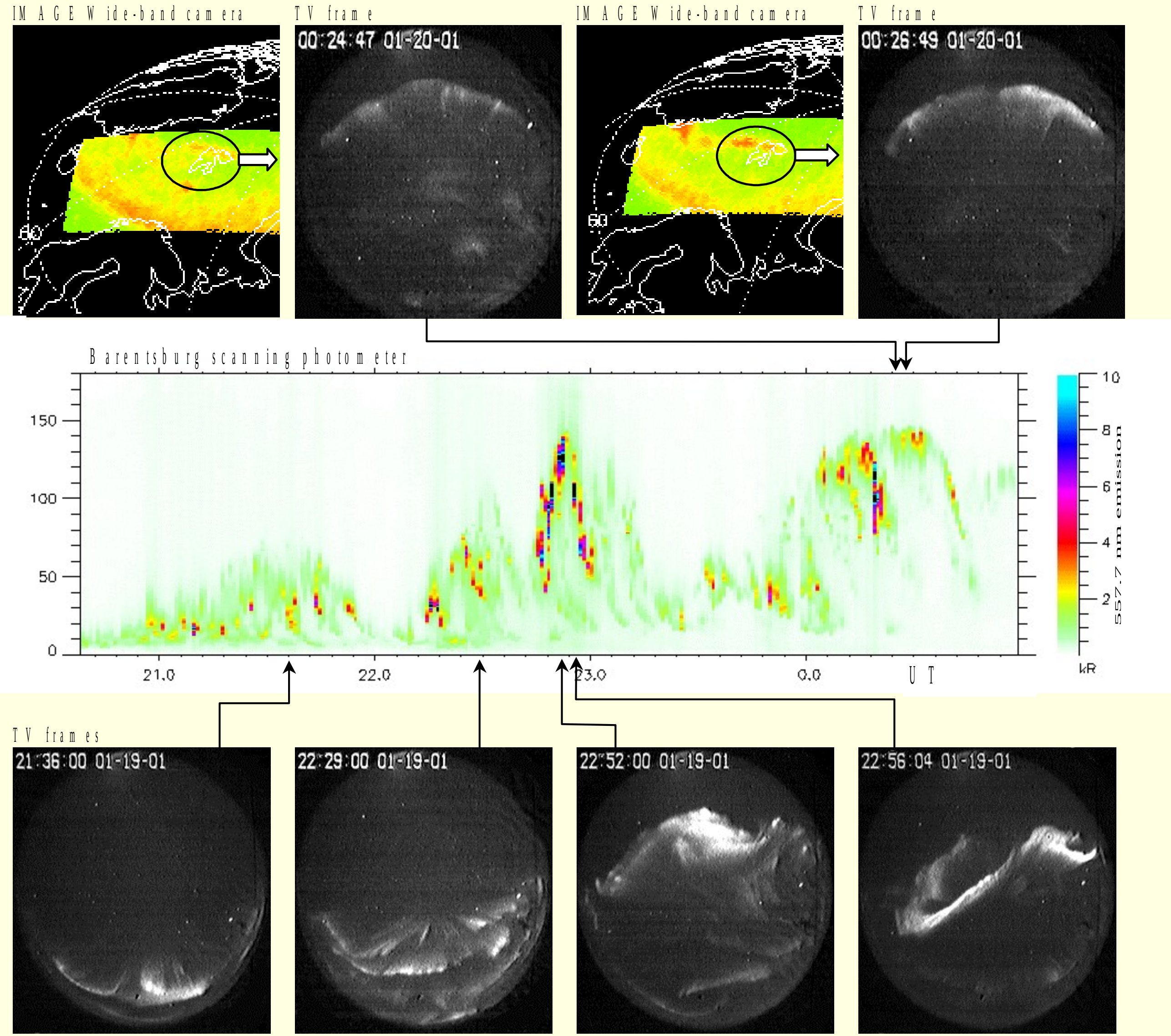
20:50-00.30UT

Bz IMF = ±2 nT

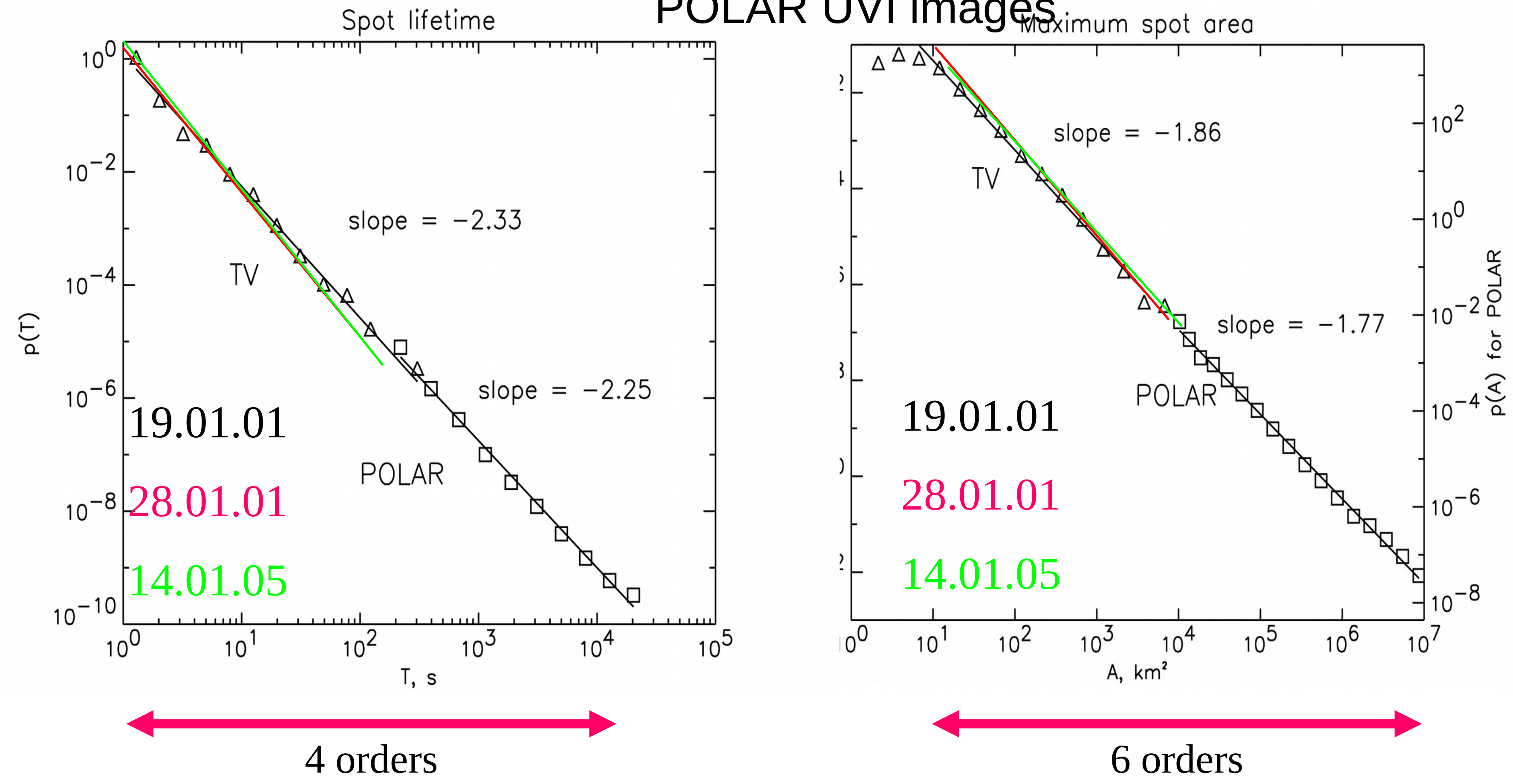
Dst = 14-22 nT

Kp = 1-2

AE < 100 nT

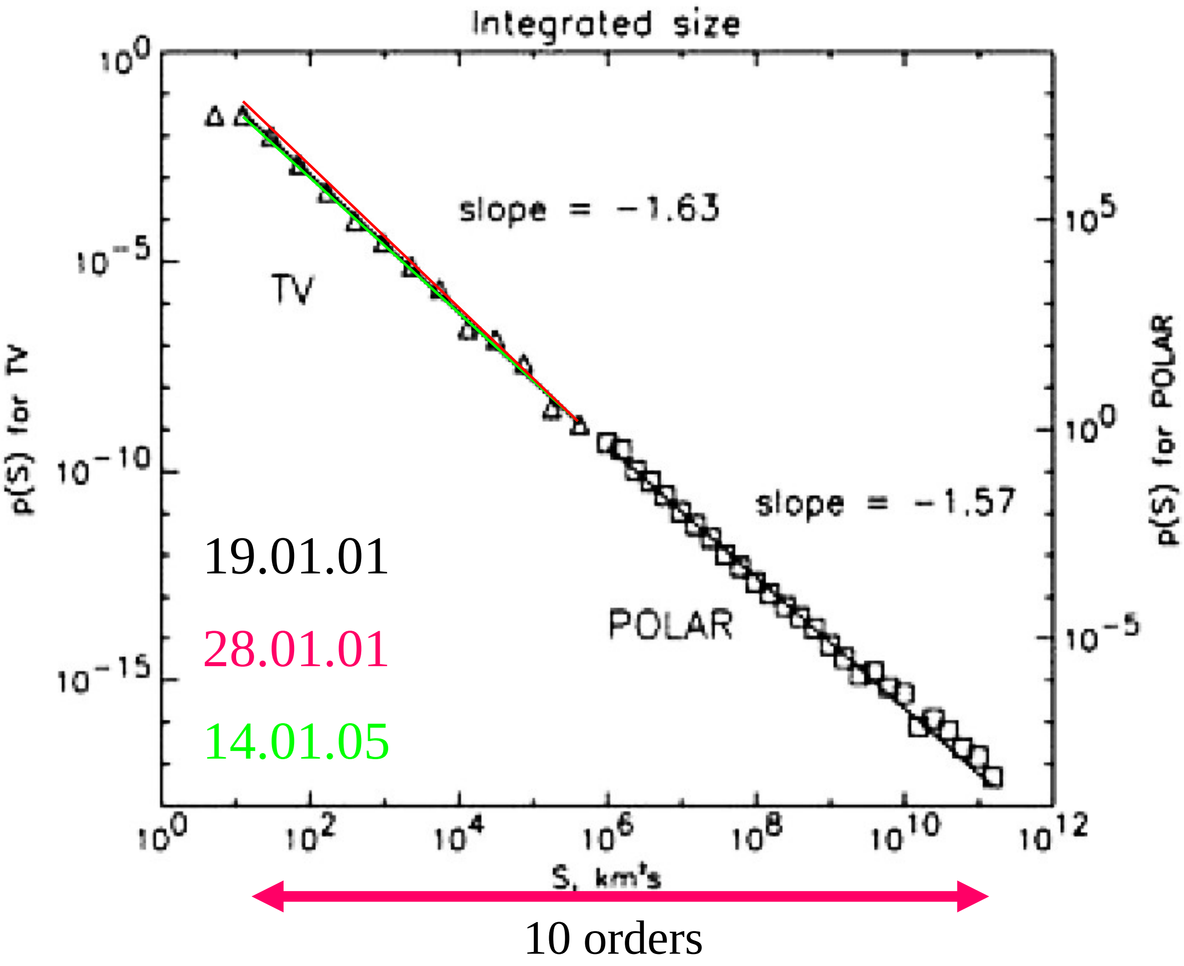


Comparison of distributions obtained by groundbased TV all-sky observations and POLAR UVI images



[B. V. Kozelov,V. M. Uritsky, and A. J. Klimas, GRL, 31, L20804, 2004]

Comparison of distributions obtained by groundbased TV all-sky observations and POLAR UVI images



[B. V. Kozelov,V. M. Uritsky, and A. J. Klimas, GRL, 31, L20804,

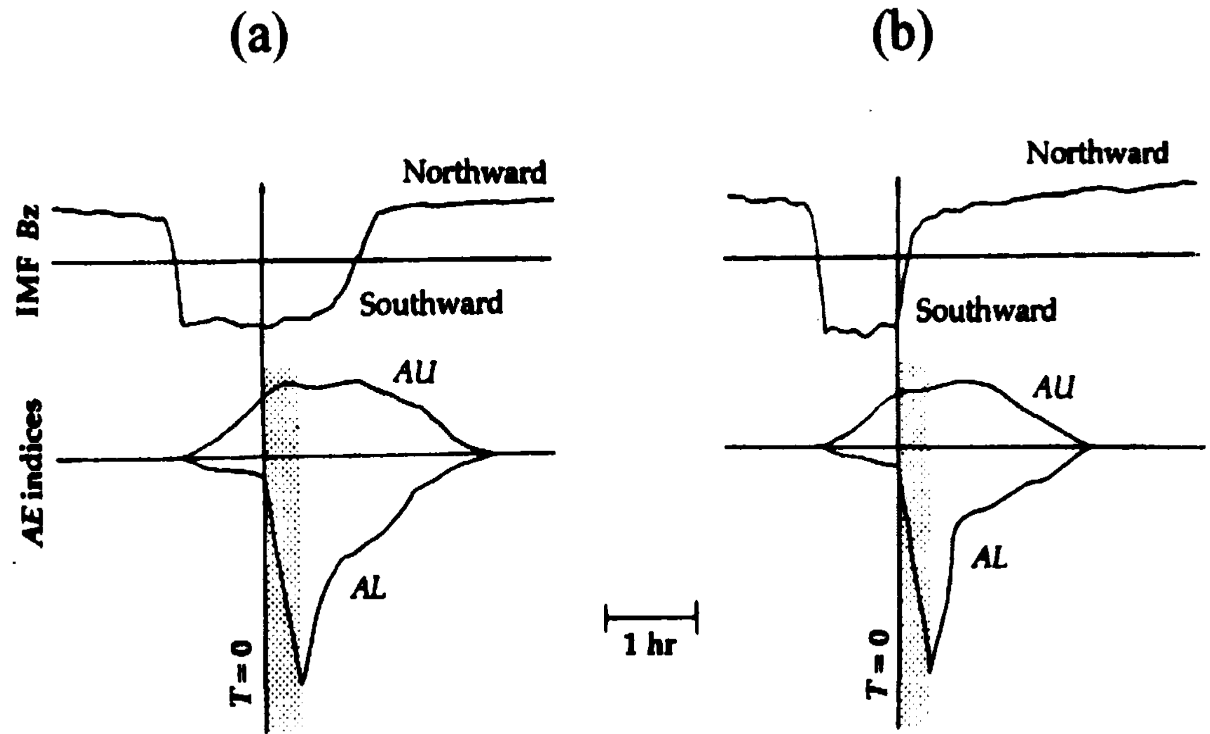
Кстати о триггировании.

Analogy with SOC system lead to obvious classification of substorm onsets.

Spontaneous (a)

locally stimulated (a)

globally stimulated (b)

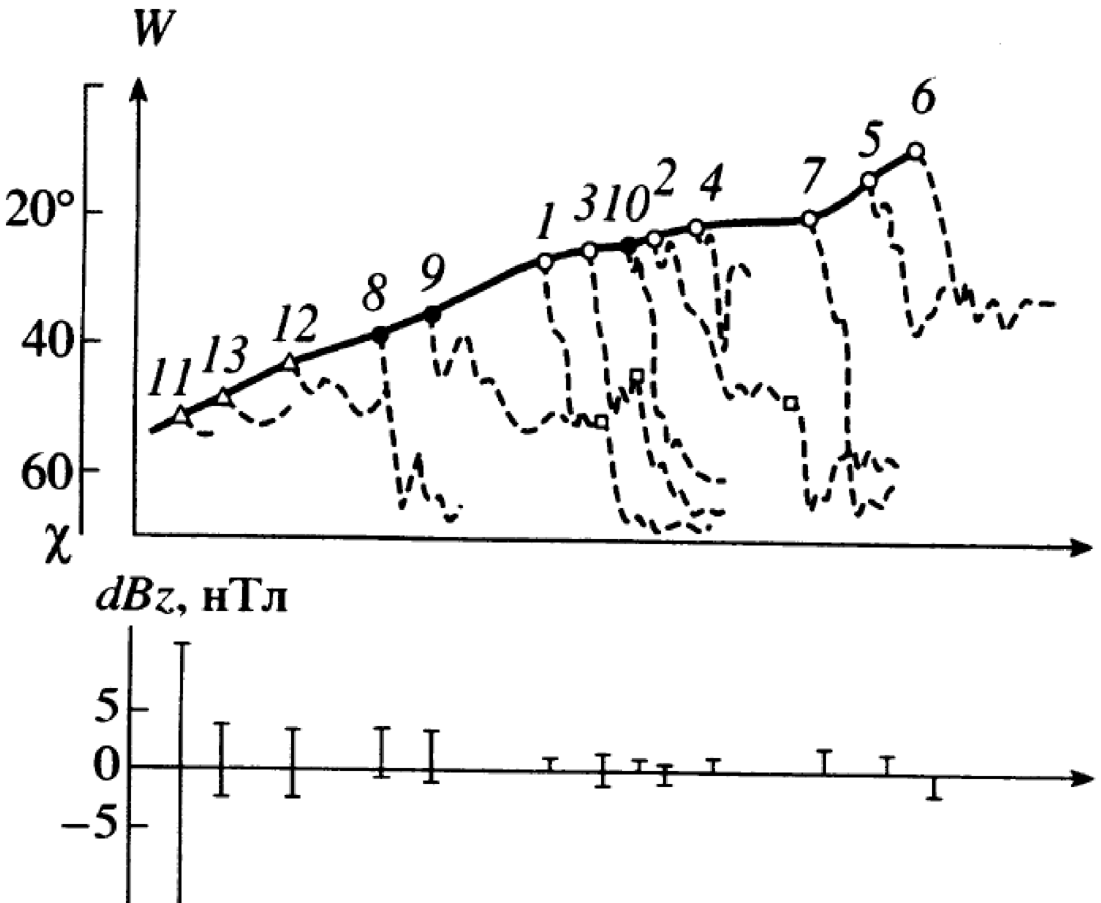


Probability of event stimulation

Schematic from [Kozelova et al., 1989]:

χ - stretching of magnetic field

dB_z - fluctuation of B_z IMF near substorm onset



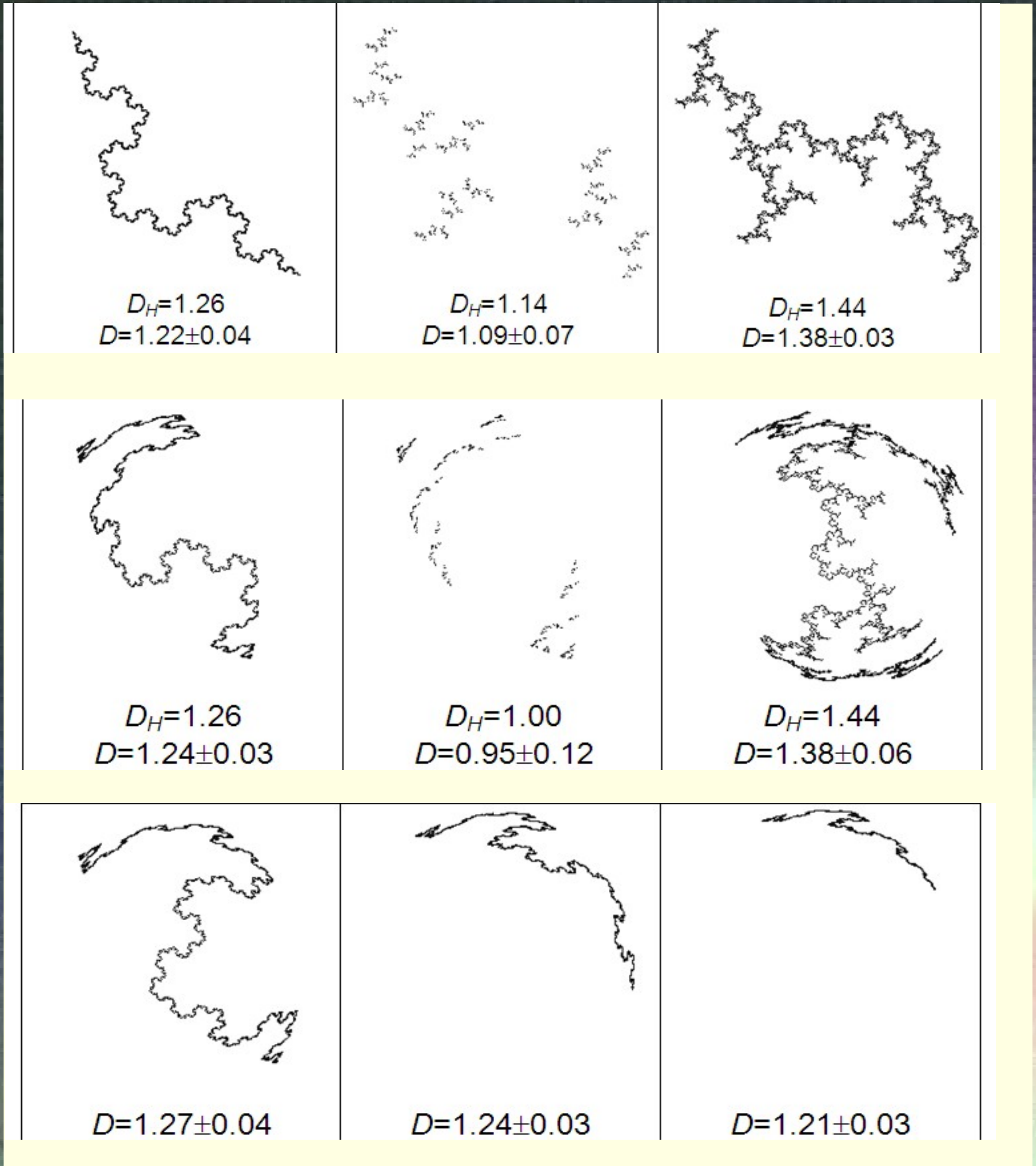
Importance of the power-law statistical distributions

- Scaling index value is invariant on distortions of camera lens. [Kozelov B.V, *Annales Geophysicae*, V. 21, P. 2011, 2003]

- Scaling index value can be corrected on aspect angle distortions. [B. V. Kozelov and I. V. Golovchanskaya, *J. Geophys. Res.*, *2009JA014484*, 2010]

- Power-law statistical distributions are typical feature of “turbulent” state.

Simulated images with prefractal structures



Geometrical distortions for all-sky images

Distortions near the horizon

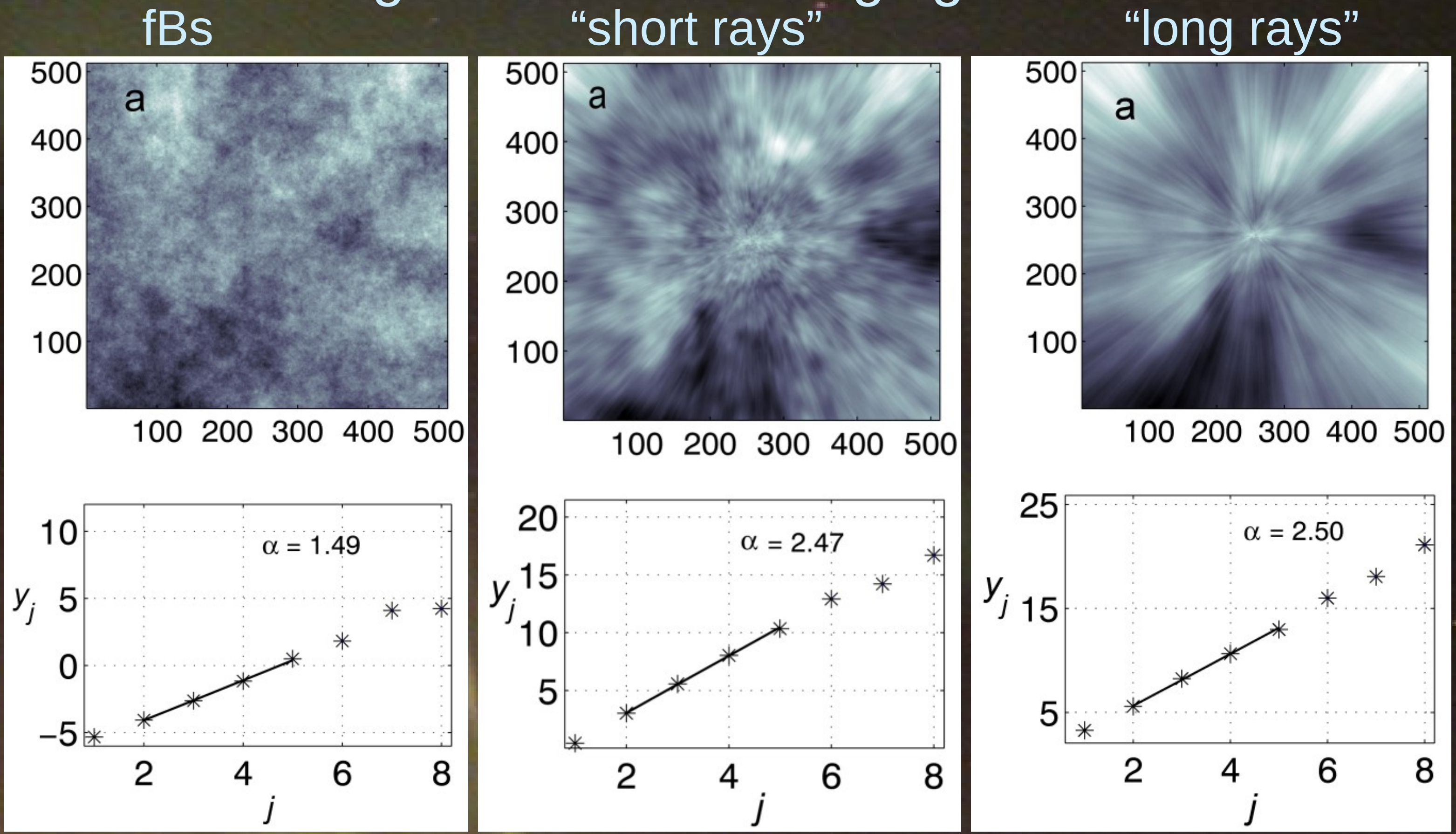
Importance of the power-law statistical distributions

- Scaling index value is invariant on distortions of fisheyes lens. [Kozelov B.V, *Annales Geophysicae*, V. 21, P. 2011, 2003]

- Scaling index value can be corrected on aspect angle distortions. [B. V. Kozelov and I. V. Golovchanskaya, *J. Geophys. Res.*, *2009JA014484*, 2010]

- Power-law statistical distributions are typical feature of “turbulent” state.

Numerical test of deriving of aurora scaling parameters from ground-based imaging observations:



Analysis of the images by Log-scale Diagrams [Abry et al., 2000] based on wavelet decomposition. *j* – log of spatial scale, y_j – log of variance of detail wavelet coefficients at scale *j*.

Importance of the power-law statistical distributions

- Scaling index value is invariant on distortions of fisheyes lens. [Kozelov B.V, *Annales Geophysicae*, V. 21, P. 2011, 2003]

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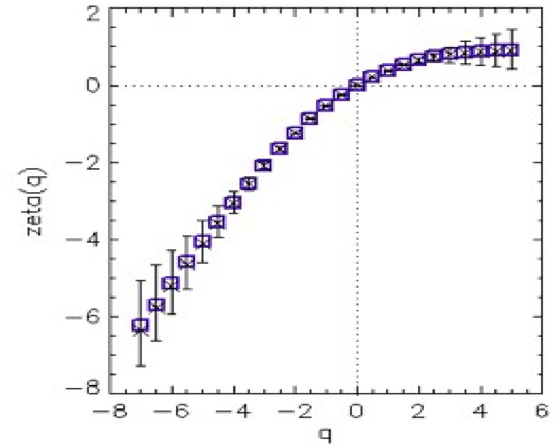
- Power-law statistical distributions are typical feature of typical “turbulent” state.

The main known results for aurora scaling

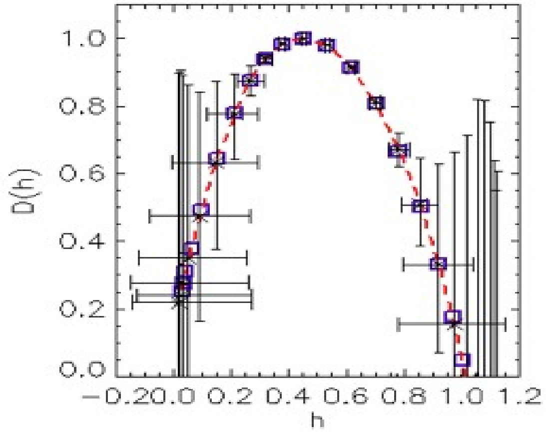
- Fractal lines of equal intensity
- SOC-like spatio-temporal statistics
- Turbulent-like spatial fluctuations
- Low-dimensional chaos

Example of MF features of vB_z (2000 year)

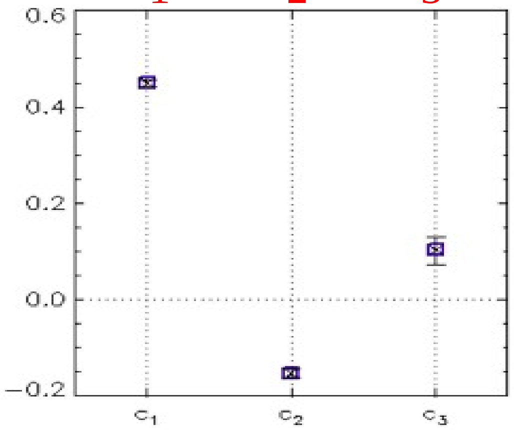
$\zeta(q)$



$D(h)$

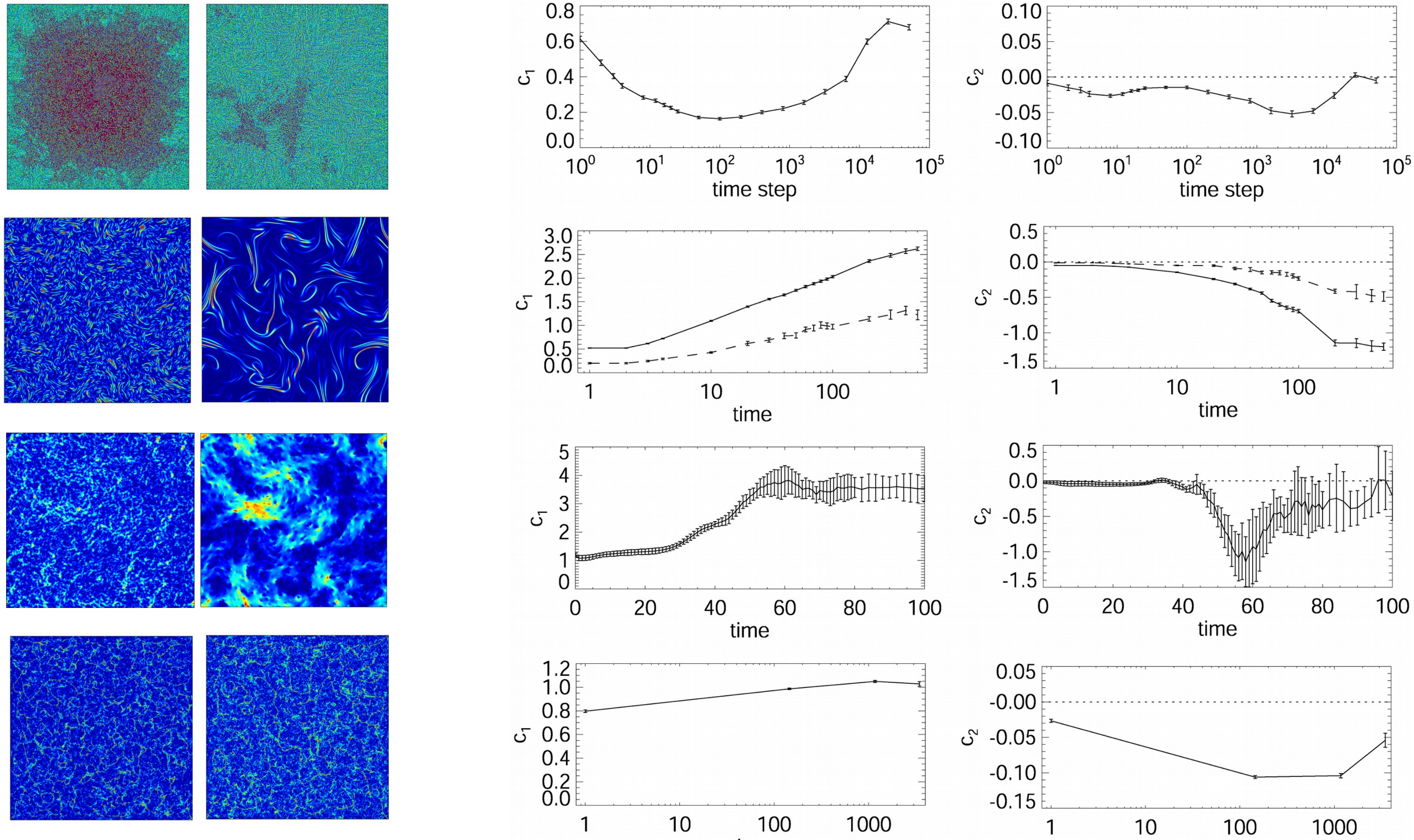


c_1 c_2 c_3



$\zeta(q)$ is estimated from linear regression of $\log Z(q,a)$ versus $\log a$ on the time scales 4-128 minutes.

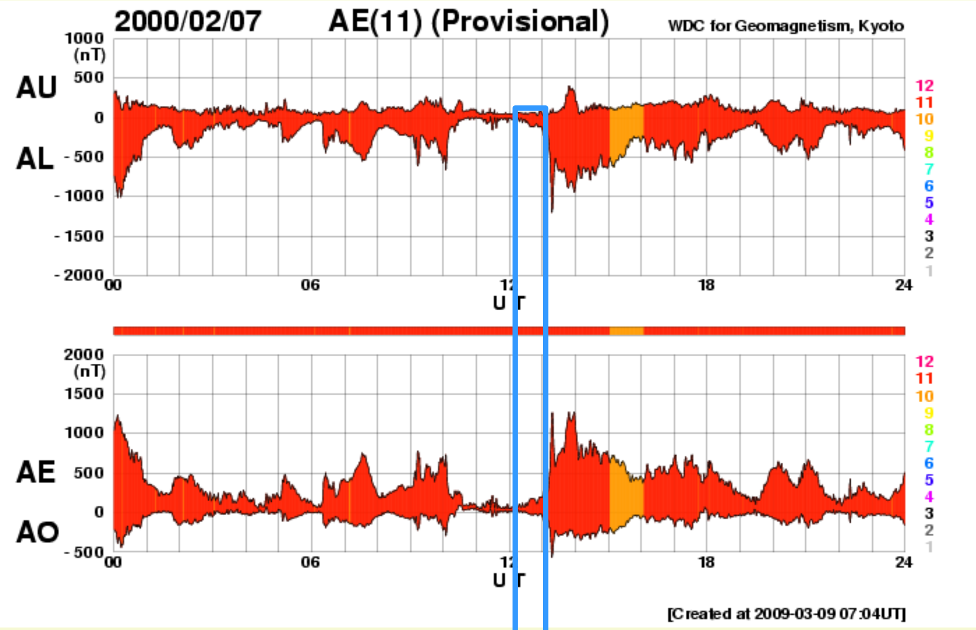
A bootstrapping technique has been employed that allows us an estimation of, and reduction of, error bars.



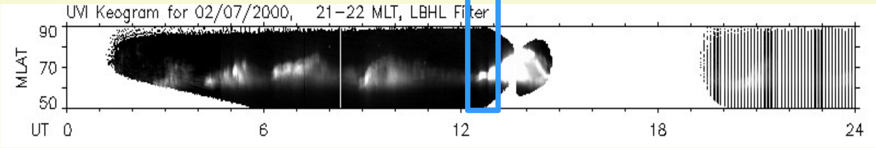
c_1
0.8
0.6
0.4
0.2
0.0
10^0 10^1 10^2 10^3 10^4 10^5
time step
c_2
0.10
0.05
0.00
-0.05
-0.10
10^0 10^1 10^2 10^3 10^4 10^5
time step
c_1
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1 10 100
time
c_2
0.5
0.0
-0.5
-1.0
-1.5
1 10 100
time
c_1
5
4
3
2
1
0
0 20 40 60 80 100
time
c_2
0.5
0.0
-0.5
-1.0
-1.5
0 20 40 60 80 100
time
c_1
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 10 100 1000
c_2
0.05
-0.00
-0.05
-0.10
-0.15
1 10 100 1000

Individual transient data analysis

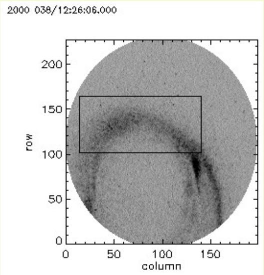
Auroral electrojet activity. Start of intensification at ~1227UT has been analyzed.

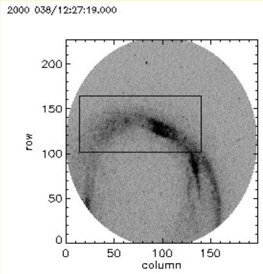


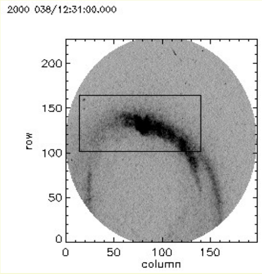
Polar UVI keogram



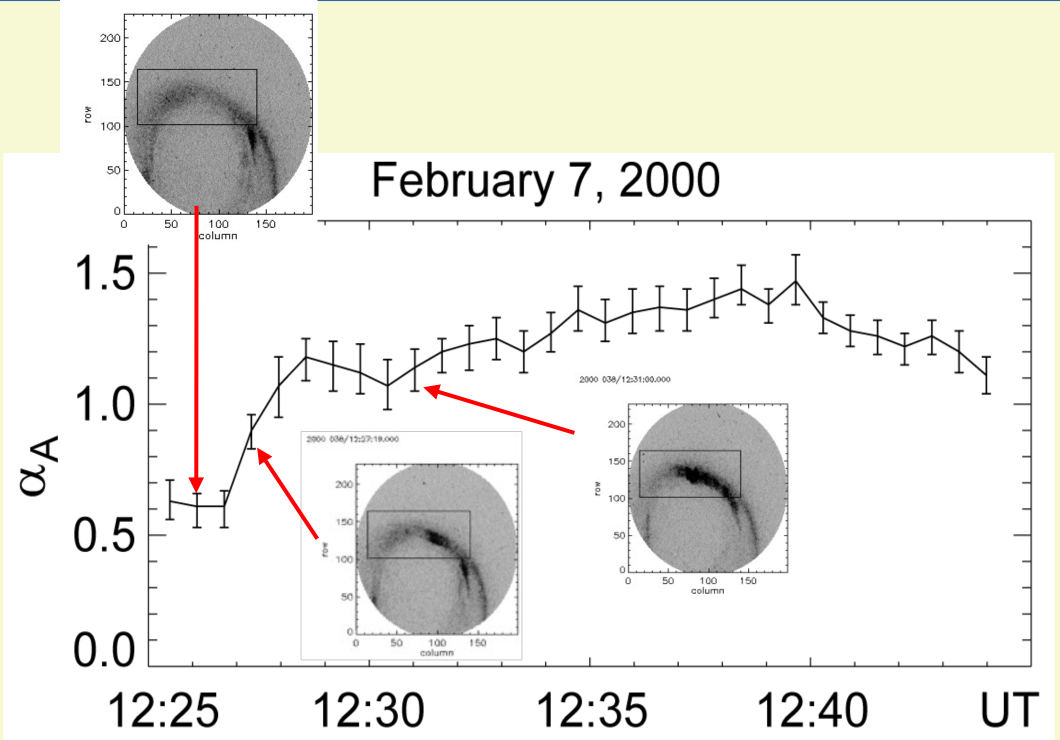
Polar UVI images

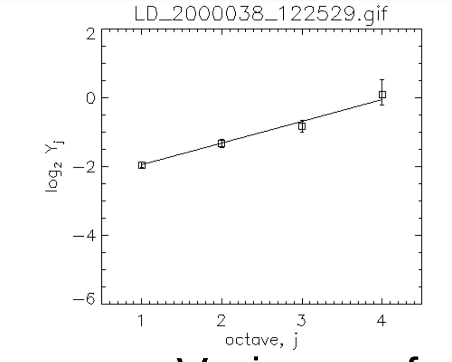


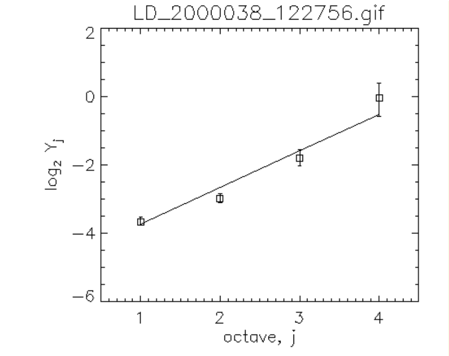


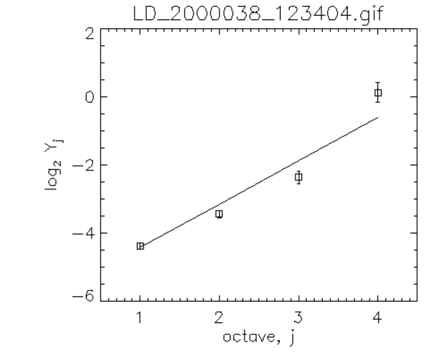


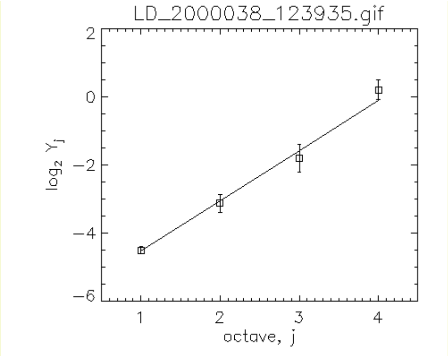
Evolution of scaling index α calculated for intensity fluctuations in the columns of marked regions of Polar UVI images.





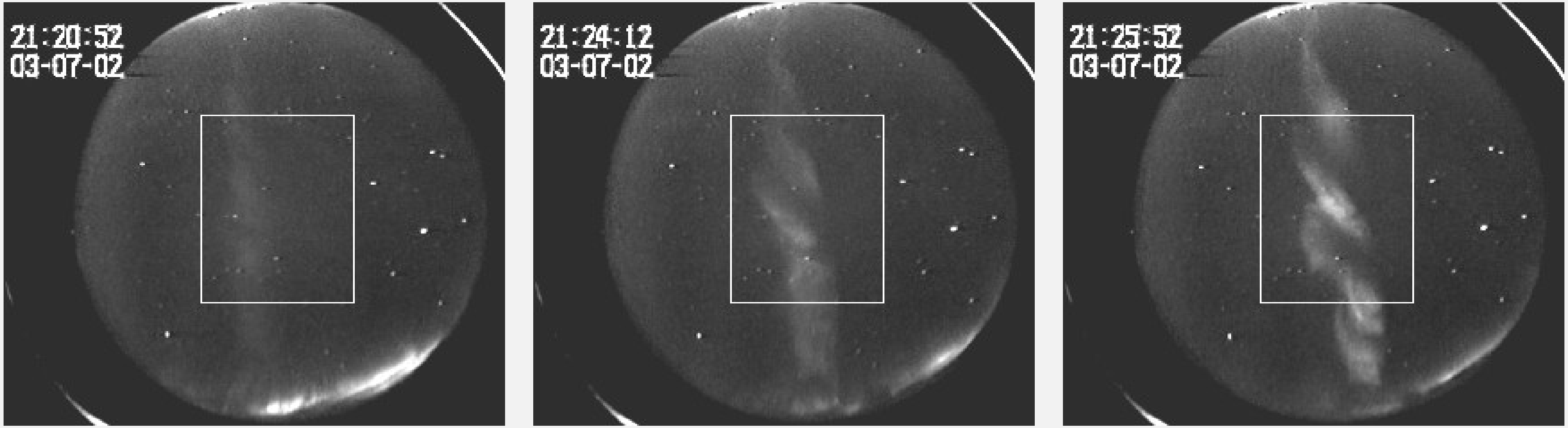






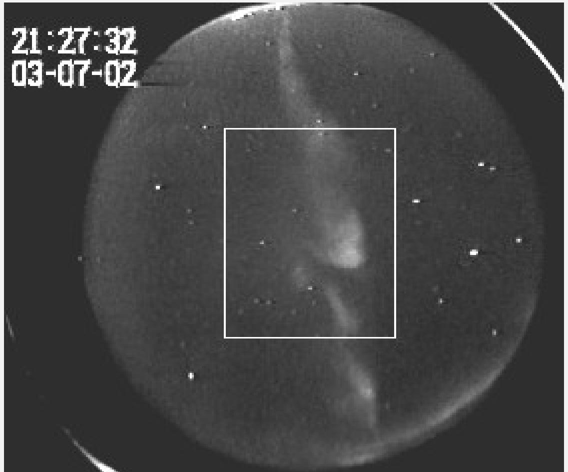
Variance of wavelet decomposition coefficients at given scale as a function of scale. The error bars - estimations by bootstrap method (95% confidence level).

TV observation of theta-aurora on Barentsburg



- Bz IMF >0, activation of polar arc:

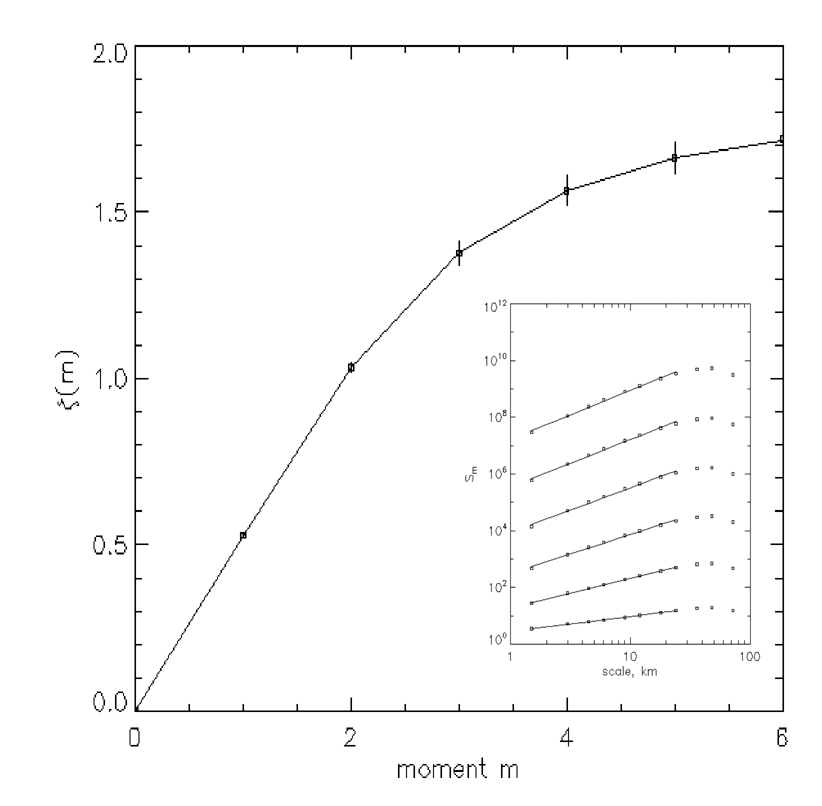
7 March 2002, 21:15-21:35 UT

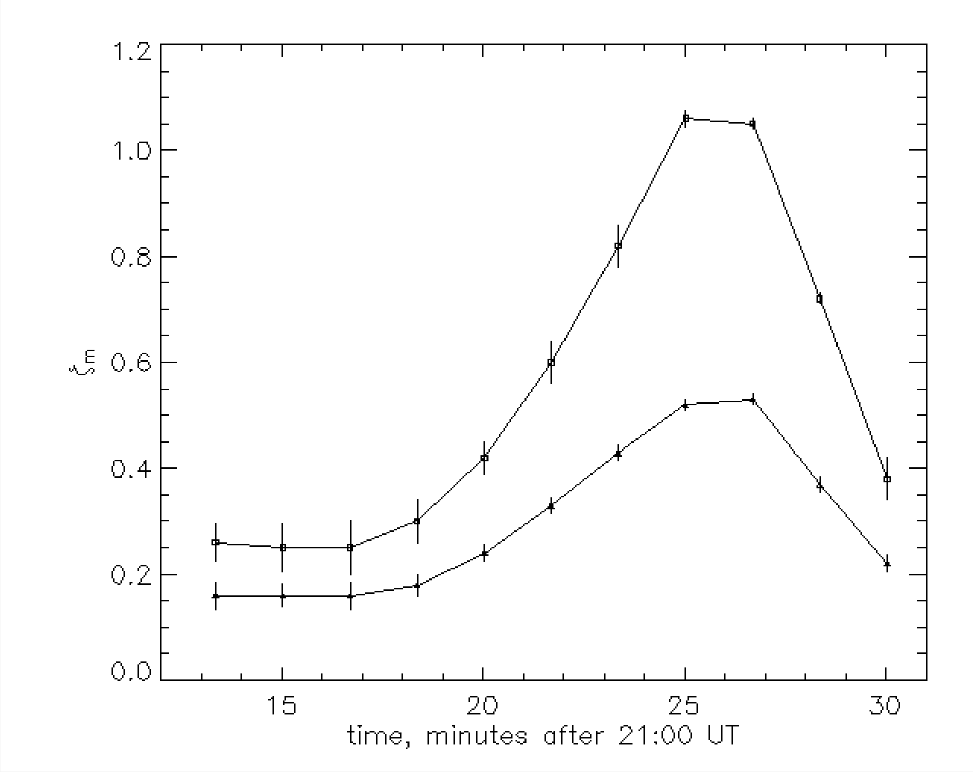


- See details of this event in [Kozelov and Golovchanskaya.

GSF analysis of luminosity variations for theta-aurora

[Kozelov and Golovchanskaya. *GRL*, V.33, L20109, 2006]

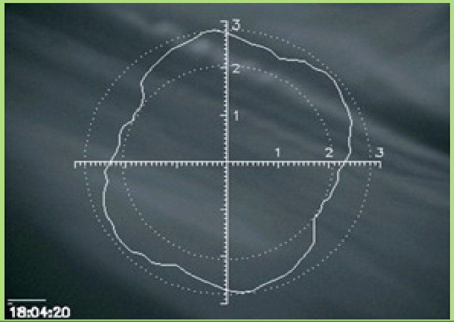




- Conditioning with A=70 has been used to decrease influence of stars.
- Power law region for scales < 30 km is observed up to 6 moment of the structure function.
- Scaling index as a function of the moment has non-linear form, that means multi-fractal structure of the signal.
- Scaling indexes are varied during the event. Maximum value of ζ_m/m was ~0.53

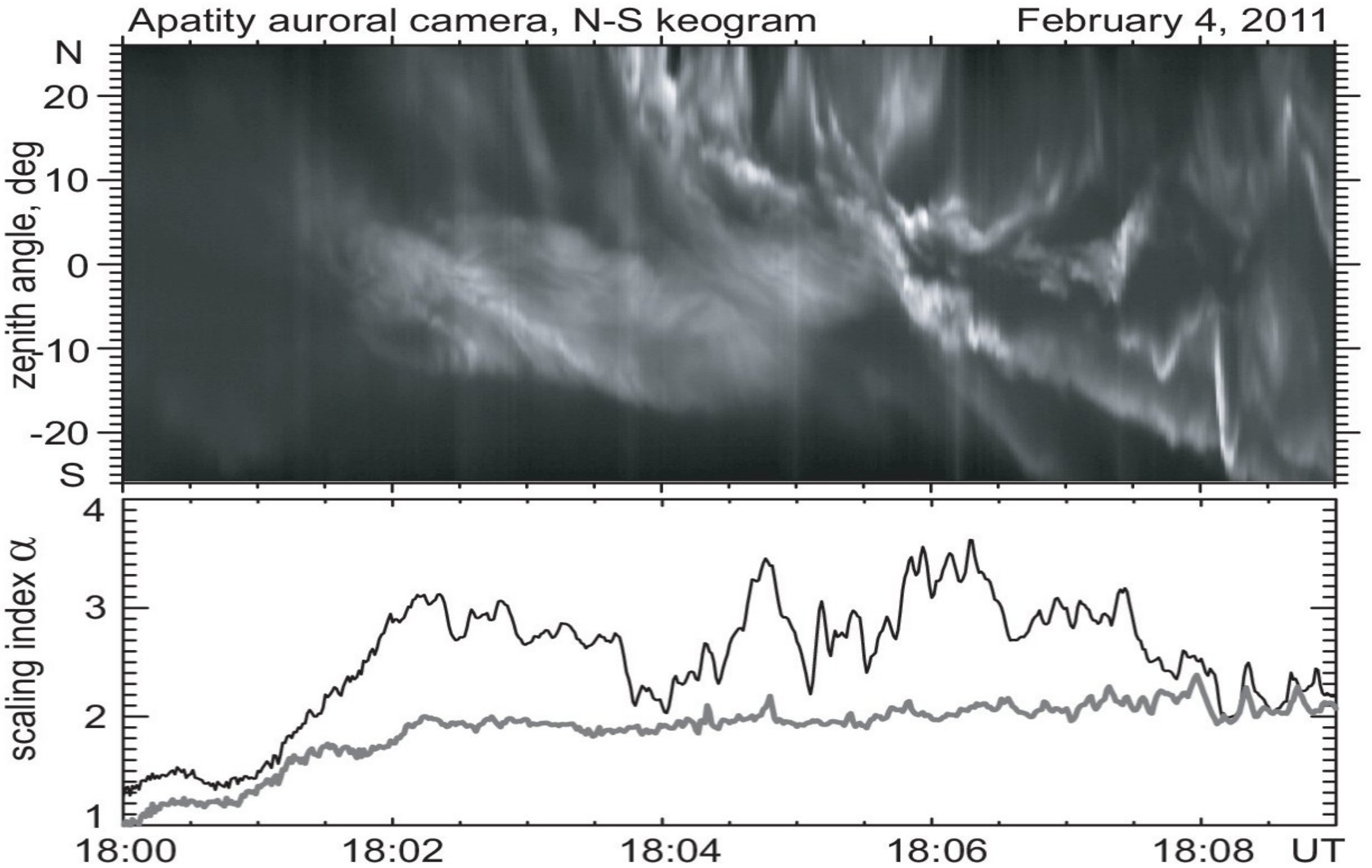
Multiscale
Aurora
Imaging
Network

Anisotropy of scaling index



Guppy-C data, green channel. The overlapped polar plots present angular dependence of the scaling index. The index value is expressed by radial distance and the angle indicates the direction of a linear cross section of the image used for index calculation.

Black(gray) line shows evolution of the scaling index for perpendicular (parallel) cross section of image



Случай 20 марта 2020, 19:42 – 19:49 UT

Для анализа использованы данные эмиссионного имажера обсерватории "Ловозеро", камера канала эмиссии 427.8 нм (EI42). Камера включает светосильный объектив ОСШ-1.0-ГАО(8.2), EMCCD камеру PhotonMax:512B, фильтровое колесо ZWOEFW5x2 с набором светофильтров (интерференционный светофильтр на 427.8 нм и адсорбционный светофильтр на группу 1NG 380-500нм).

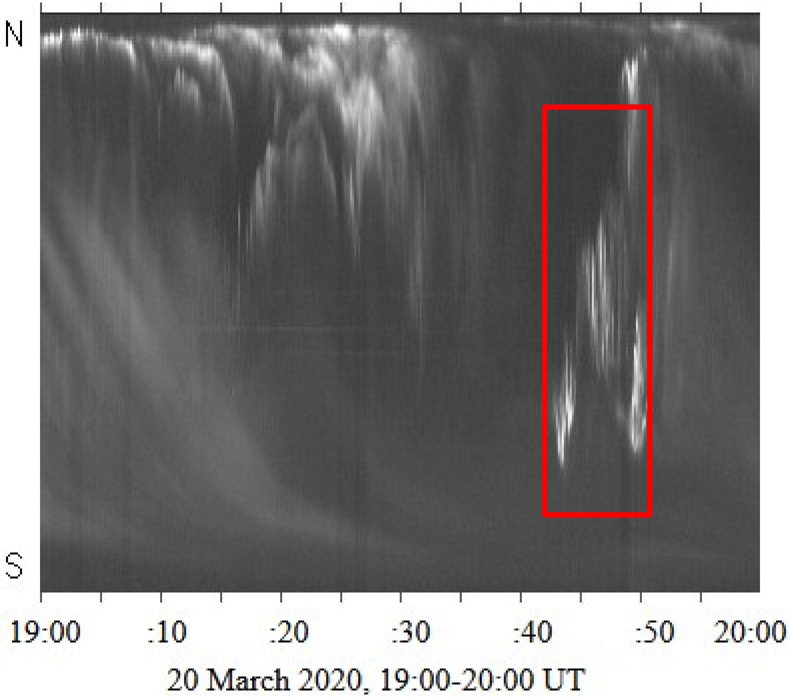
Прибор обеспечивает: поле зрения - 180 град., угловое разрешение - до 0.35 град., разрядность АЦП - 16 бит, временное разрешение - 0.1 сек. с синхронизацией экспозиции от системы GPS

Регистрация проводолась под пролеты спутника ARASE.Всего в этом случае имеем 4095 кадров.

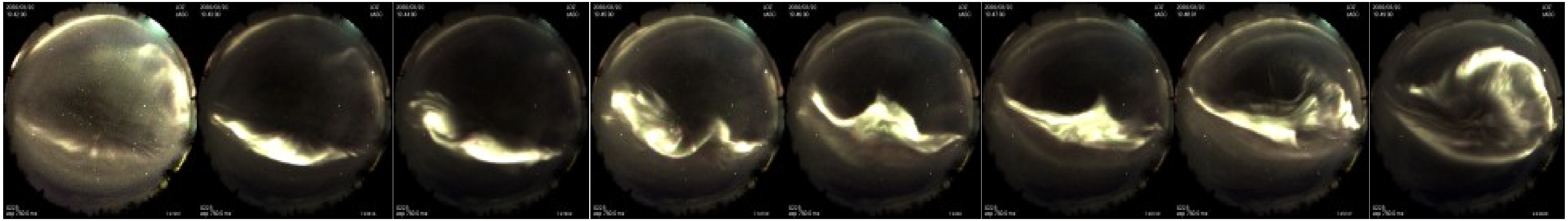
Процедура обработки:

1.Ограничение поля зрения до 75^{o} от зенита и ограничение по уровню интенсивности.
2.Выделение связных кластеров на каждом кадре.
3.Прослеживание истории кластеров во времени.
4.Определение начального и конечного момента для каждого кластера, максимальной площади (с учетом искажение объектива) каждого кластера в течение его истории, интегрированной площади каждого кластера.
5.Вычисление распределений, выделение степенных участков.

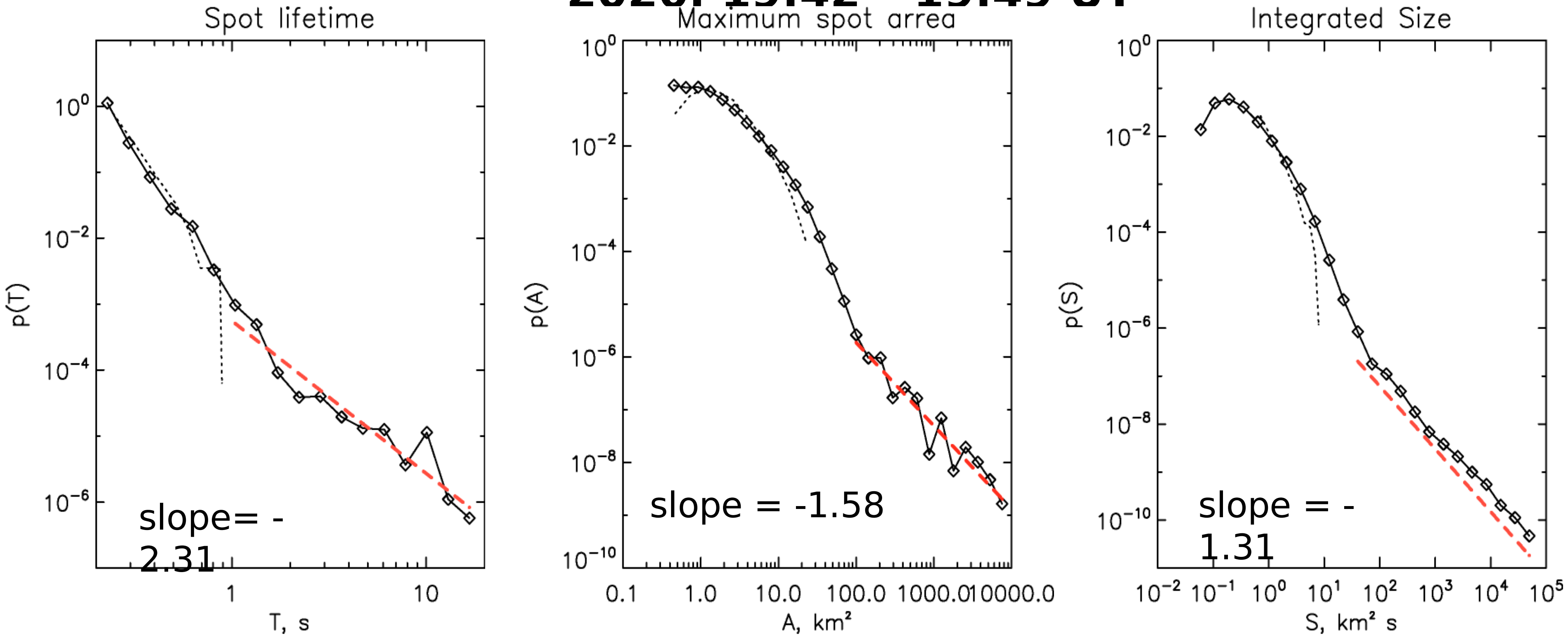
Apatity AS (panchromatic) keogram



Динамика сияний по данным RGB камеры всего неба в Ловозеро



Статистические распределения для случая 20 марта 2020. 19:42 – 19:49 UT



В рассмотренном интервале выделено 83375 пространственно-временных кластеров (пятен). В распределениях на малых масштабах видно изменение формы распределений (сплошные линии с ромбами). Контрольная обработка последовательности кадров с закрытым затвором показало, что распределения на малых масштабах определяются шумом детектора (мелкий пунктир). На больших масштабах на распределениях выделены степенные участки (красный пунктир), показатели приведены. Пик около 10 с на распределении времен жизни демонстрирует присутствие пульсаций во время активизации сияний.

Выводы

1. Авроральный овал отражает динамику магнитосферно-ионосферной системы.
2. Существующие модели не описывают внутреннюю структуру авроральных потоков заряженных авроральных частиц.
3. Наряду с регулярными структурами (дуги, пульсирующие пятна) в структуре авроральных высыпаний присутствует самоподобие (степенные распределения), как в статистических распределениях, так в индивидуальных переходных процессах.
4. Описание этих структур возможно включить в модель.

Осложнения:

1. Анизотропия фрактальных характеристик.
2. Мультифрактальность транзиентов.


Thank you for attention!