

Is the dynamic magnetosphere an avalanching system?

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Abstract. The analogy between the dynamic magnetosphere and an avalanche system is examined by using the global auroral energy deposition obtained by the Polar UVI as a measure of the energy output of the magnetosphere. The analysis reveals two types of energy dissipation: those internal to the magnetosphere occurring at all activity levels with no intrinsic scale, and those associated with active times corresponding to global energy dissipation with a characteristic scale. The internal events exhibit the same power law index in both active and quiet times. These features are consistent with a simple avalanche ('sandpile') numerical model.

1. Introduction

The magnetosphere is the near-Earth environment loaded with energy from the interaction with the highly variable solar wind. Part of this energy is in turn dissipated by particle precipitation into the ionosphere giving auroral displays and as magnetic disturbances. At times, these disturbances can disrupt radio communications and cause spacecraft malfunctions.

The dynamics of Earth's magnetosphere can be sampled both internally via *insitu* spacecraft observations, and remotely sensed over extended time periods by ground-based or space-borne instruments, making it unique amongst astrophysical plasma systems. Internal signatures of plasma transport are bursty [e.g., Lui, 1991; Angelopoulos *et al.*, 1997] and correspond to auroral structures in a range of small scales seen during all levels of magnetospheric activity [Akasofu, 1965]. Distinct from these both in their auroral and ground-based signatures are global events, substorms and storms, that deposit significant amounts of energy into Earth's immediate space environment. The largest scale events, i.e., storms, are directly correlated with strong driving by the solar wind [Fox *et al.*, 1998]. The causal relationship between the solar wind variability and both substorms and internal events is not well understood.

Magnetospheric dynamics is known to be nonlinear and complex. The low dimensionality of the dynamics [e.g., Sharma, 1995; Klimas *et al.*, 1996], the power law power spectra exhibited by the magnetic field measured *in situ* in the geomagnetic tail [Lui *et al.*, 1992], and the bursty nature of plasma transport and dissipation have recently led to the suggestion that the magnetosphere evolves through nonequilibrium states, dissipating energy by means of avalanches on all scales and may in addition be in a self organized critical (SOC) state [e.g., Chang, 1992; Consolini *et al.*, 1996; Chapman *et al.*, 1998]. This approach predicts that the energy released, the size and the duration of events should have a power law probability distribution [e.g., Jensen, 1998].

Analysis of the substorm activity index derived from ground-based magnetic field measurements, the AE index, yields indeed a power law probability distribution [Consolini, 1997]. There are however several intrinsic limitations of the AE index which make it unsuitable as an accurate measure of the system energy output. These include the incomplete and nonuniform coverage in both latitude and longitude from the twelve magnetic stations chosen to construct the AE index and the sensitivity of activity location relative to the stations since the AE index is an envelope of all magnetic perturbations. Ground-based magnetic field measurements are also a secondary measure of precipitation and currents flowing in the aurora overhead and hence also include the conductivity uncertainties from solar UV illumination and the precise locations of the auroras.

In this paper, we use global images of auroras from the vantage point of a satellite to monitor the energy output over the entire magnetospheric system directly. It has previously been established that on the smallest scale, such as fine auroral arcs of width ~ 100 m, the power output depends on the details of magnetosphere-ionosphere coupling while on the largest scale, the global auroral power averaged over an hour or so correlates well with solar wind input. There is apparently no previous investigation for all scales. We obtain here for the first time the probability distributions in power and spatial size of the output from the magnetosphere system for all scale sizes. These distributions are extremely robust, quite independent of the criteria used to define an auroral activity region. We present here evidence that the full range of system dynamics, from small scale internal relaxations to global reconfigurations, resemble those of a simple avalanche system. This result bears important implications on the predictability of space weather activity at Earth.

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2. Analysis

A representative global auroral image obtained by the UV Imager [Torr *et al.*, 1995] on the Polar spacecraft is given in Fig. 1 with the auroral intensity represented by a false color scale. The continental outline is also provided to guide the determination of the auroras's locations. Typically, there are several spatially distinct regions of auroral activity. To perform the analysis on the auroral images, we use a dewobbling routine to correct for the smearing of auroral images due to the nutation of the satellites spin axis. We then transform the images onto a Mercator projection of magnetic latitude (MLat) and magnetic local time (MLT) at an assumed emission altitude of 120 km. A cosine factor is used to compensate the Van Rhijn effect that results from the unequal optical lengths in the field of view. Fig. 2a shows the auroral distribution for the MLat range of 55° to 90° and the MLT range of 20 to 02 through midnight. The use of nighttime observations eliminates the uncertainties added by the dayglow. To determine the distribution of power and sizes of these auroral activity regions, we first obtain the background intensity in the polar region outside the luminous auroral belt and subtract it from the intensity in the auroral belt. We then identify individual auroral blobs by applying an intensity level corresponding to a threshold well above (ten times) the instrument noise level; the following result remains unchanged with other thresholds used. Fig. 2b shows the identification with each auroral blob shown in a separate color. The power [Germany *et al.*, 1997] in the auroral intensity and the area of each blob are then calculated and compiled into the statistics. We

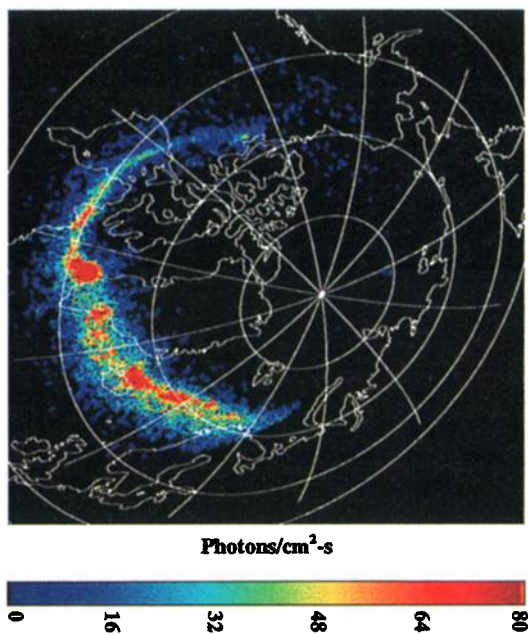


Figure 1. A sample of global auroral distribution from the Polar UV Imager.

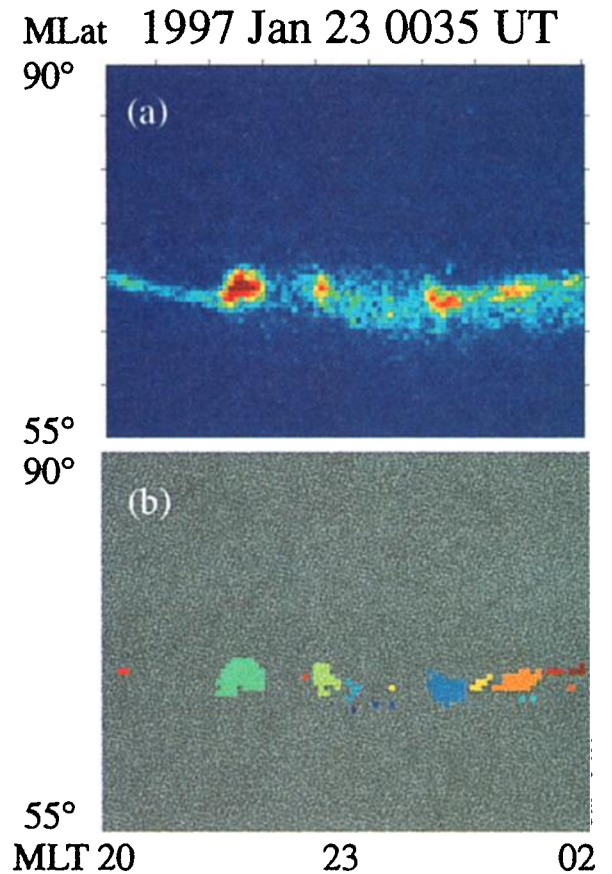


Figure 2. Analysis of an auroral image from Polar: (a) auroral distribution is transformed into coordinates of MLat and MLT, (b) identification of individual auroral activity region.

also visually inspect each individual image to sort them in terms of substorm and quiet time categories to isolate the effects of substorms on the power and area distributions.

We perform the above analysis for the entire data set of January 1-31, 1997, consisting of 9,033 frames of auroral images. This period includes a major storm on January 10-11, 1997 which has been extensively analyzed by the international space community [e.g., Fox *et al.*, 1998]. The normalized distributions in the auroral blob size are shown in Fig. 3a,b. The total number of auroral blobs is 81,794 for quiet time (Fig. 3a) and 155,347 for substorm intervals (Fig. 3b). We sort the distributions in five bins per decade. The upper range of the area is limited by the total viewing scope of the instrument while the lower range by the instruments spatial resolution and sensitivity. For quiet time intervals, the area distribution shows a power law dependence with a slope of -1.161 ± 0.033 . For substorm intervals, the distribution shows a prominent peak above $\sim 10^5$ km². Between $\sim 5 \times 10^3$ and $\sim 5 \times 10^4$ km², there is indication of a power law with a slope of -1.206 ± 0.079 . Therefore, within the bounds of uncertainties, the two power law slopes are similar.

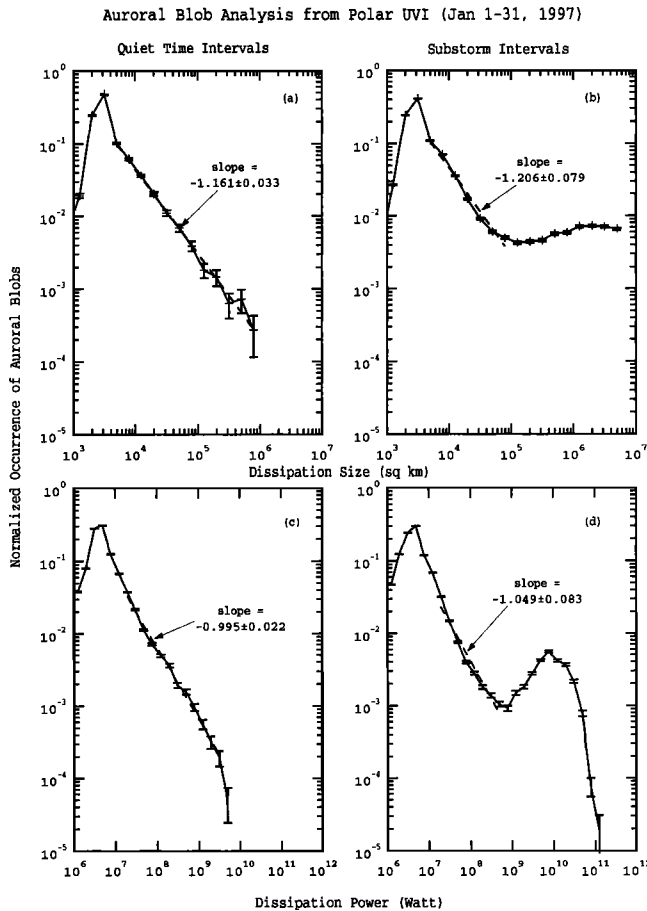


Figure 3. Probability distribution of size and power output of individual auroral region. (a) size distribution during quiet times. (b) size distribution during substorms. (c) power distribution during quiet times. (d) power distribution during substorms.

The distributions of the dissipation power indicated by the auroral blob intensity are shown in Fig. 3c,d. These distributions resemble remarkably well the size distributions of auroral blobs. During quiet time (Fig. 3c) the dissipation power has a power law with a slope of -0.995 ± 0.022 . Similarly, there is a peak in the distribution for substorms (Fig. 3d) at the dissipation power exceeding $\sim 5 \times 10^8$ Watt. Between $\sim 5 \times 10^6$ and $\sim 5 \times 10^8$ Watt, the distribution has a slope of -1.049 ± 0.083 .

The power law distribution and the similarity in the slope value for both the size and dissipated power of events for quiet time and for substorms suggest that there is an ever-present component of auroral activity which exhibits the scale free (power law) size distribution of an avalanching system regardless of the presence or absence of substorms, and hence independent of the level of activity in the system. We interpret these power law distributed events as bursty, internal (localized) relaxations of the system. The other events, which show well defined distribution peaks in terms of power dissipated and size, are interpreted as global reconfigurations.

The above results may be compared with simple avalanche (sandpile) models. Recently, it was demonstrated that an avalanche model can exhibit power law statistics in the energy released by internal relaxations, whereas the energy released from global reconfigurations is distributed around a characteristic mean which scales with the system size [Chapman *et al.*, 1998]. These correspond to the internal and substorm events identified in the auroral data, respectively. For a direct comparison, the avalanche model [Chapman *et al.*, 1998] was run with fluctuating input (to mimic the solar wind, see also [Watkins *et al.*, 1999; Chapman *et al.*, 1999]) and here in Fig. 4 the output of all events, both internal and global, are shown on a single plot. The internal events fall on a power law which maintains the same slope independent of the driving rate [Watkins *et al.*, 1999; Chapman *et al.*, 1999]. The effect of fluctuations in the input is to distort the lowest energy events giving an increase in slope; this can also be seen on the auroral data (Fig. 3). Finally the global events appear as a statistically significant peak at the high energy end. In intervals of data containing substorms we would then expect to see a power law at lower energies/sizes and a peak at higher energies/sizes. In data intervals that do not contain substorms we expect a power law distribution with the same index, and no peak to be present. The avalanche model output is hence consistent with what we see in the auroral imaging data.

3. Conclusion

We have used the global auroral imagery to obtain, for the first time, the statistics of size and energy dissipated by the magnetosphere system as represented by the intensity of auroral emission on a world-wide

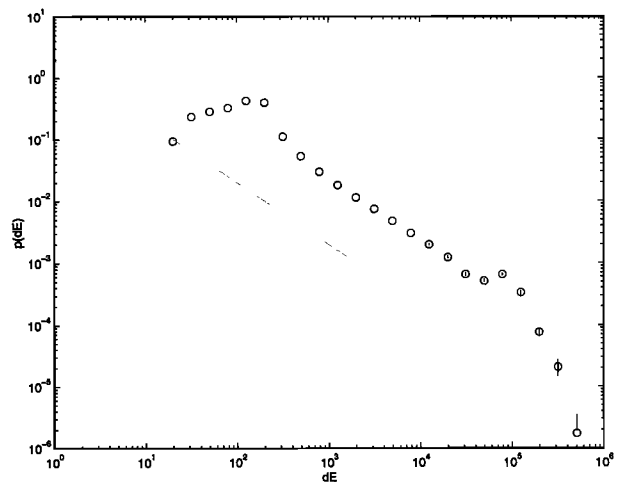


Figure 4. Probability distribution of a sandpile model. The internal avalanches have a power law distribution with no intrinsic scale whereas the system-wide avalanches show a characteristic scale. The solid line has a slope of -1 for comparison.

scale. We find that the internal relaxations of the magnetosphere statistically follow power laws that have the same index independent of the overall level of activity, and that both the internal and global events are consistent with the behaviour of a finite size avalanche model. This implies that the rich array of auroral phenomena is an indication that the coupled solar-wind-magnetosphere system is out of equilibrium, evolving via avalanches which have no intrinsic scale. A class of such systems is in a self organized, critical state. The onset of local avalanches in the sandpile model can be physically related to the merging of coherent structures around Alfvénic resonances [Chang, 1998, 1999] or current disruption by kinetic instabilities [Lui, 1996] in the magnetotail.

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