Nat. Hazards Earth Syst. Sci. Discuss., 2, 3183–3192, 2014
www.nat-hazards-earth-syst-sci-discuss.net/2/3183/2014/
doi:10.5194/nhessd-2-3183-2014

Natural Hazards and Earth System Sciences Discussions
Open Access

Statistical similarity between high energy charged particle fluxes in near-earth space and earthquakes

P. Wang, Z. Chang, H. Wang, and H. Lu

Institute of High Energy Physics, Chinese Academy of Science, 100049 Beijing, China

Received: 25 February 2014 – Accepted: 28 March 2014 – Published: 5 May 2014

Correspondence to: P. Wang (pwang@ihep.ac.cn)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

It has long been noticed that rapid short-term variations of high energy charged particle fluxes in near-Earth space occur more frequently several hours before the main shock of earthquakes. Physicists wish that this observation supply a possible precursor of strong earthquakes. Based on DEMETER data, we investigate statistical behaviors of flux fluctuations for high energy charged particles in near-Earth space. Long-term clustering, scaling, and universality in the temporal occurrence are found. There is high degree statistical similarity between high energy charged particle fluxes in near-Earth space and earthquakes. Thus, the observations of the high energy particle fluxes in near-Earth space may supply a useful tool in the study of earthquakes.

1 Introduction

Recently, rapid short-term variations of high energy charged particle fluxes, which were referred to as "particle bursts" (PBs), in near-Earth space were found more frequently occur several hours before the main shock of strong earthquakes (Galper et al., 1995; Aleksandrin et al., 2003; Sgrigna et al., 2005; Fidani et al., 2010; Sidiropoulos et al., 2011; Anagnostopoulos et al., 2012). This research suggests a new possible precursor of strong earthquakes and shows potential advantage over other precursors. Further study (Wang et al., 2012) indicated positive correlations between earthquake magnitude and occurrence frequency of PBs while approaching strong earthquakes.

Although great efforts have been dedicated to the governing mechanism of the complex spatiotemporal behavior of earthquakes, it is far away to get a reliable earthquake precursor. However, concepts and methods from statistical physics have provided deep insight into the understanding of the universal behavior of earthquakes. The number of earthquakes N with a magnitude $M(\geq m)$ is given by the Gutenberg–Richter law (Ishimoto and Iida, 1939; Gutenberg and Richter, 1944). Gutenberg–Richter law states that the N (for $M \geq m$) satisfies the formula $\log N \propto -bm$, where $b \simeq 1$ (Frohlich and Davis,

NHESSD
2, 3183–3192, 2014

1993; Kagan, 1999). The number of earthquakes per unit time decreases as a power law since the sudden rise of activity provoked by a main shock. Short-range temporal correlations between earthquakes are expressed by Omori–Utsu law (Omori, 1894; Utsu, 1971).

In this paper, we show that PBs within short time window around seismic events and earthquakes share almost the same universal statistical properties. The occurrence frequency of corresponding PBs plays the same role as the energy dissipated in earthquakes does in statistical seismology. It should be noted particularly that this statistical similarity does hold true only for a relatively shorter time window.

The rest of the paper is organized as follows. In Sect. 2, we present a brief description on the data of the DEMETER (Detection of Electro–Magnetic Emissions Transmitted from Earthquake Regions) observation. In Sect. 3, we investigate statistical properties of high energy charged particle fluxes in near-Earth space. Section 4 is devoted to the conclusions and remarks.

2 DEMETER data

To study this analogy, we analyze the PBs frequency fluctuations. The PBs frequency fluctuation is defined as $Z_{\Delta n} = k_{n+\Delta n} - k_n$, where k_n is the total number of occurrence counted in time window centered around the nth seismic event. Here seismic events are arranged in order of time and Δn is a time scale of discrete interval between two seismic events.

DEMETER is the first of its kind in the micro satellite series, which aims at research on space electromagnetic and high energy particle precursors associated with strong seismic events (Sauvaud et al., 2006). We select DEMETER data with electron energy $E = 0.97$–2.3 MeV under survey mode ranged in time from 2005 to 2010. The seismic data are supplied by the IPGP (Institut de Physique du Globe de Paris).

Both seismic events and trapped particles are selected with McIlwain L parameter $1.3 \le L \le 1.4$. The PBs are identified by current counting rates which exceed 4 standard deviations from average value of the background fluxes. Furthermore, higher counting rates region of satellite orbits (lat : $-90^\circ \sim 0^\circ$, lon : $-100^\circ \sim 45^\circ$) are excluded from consideration.

As in survey mode all orbit-related parameters are provided every 28 s, so counting rates are averaged every 28 s and each PB at least experiences a period of 28 s. For one PB lasting over 28 s and still staying in the region $1.3 \le L \le 1.4$, it will be regarded as two or more PBs depending on its time duration (see Fig. 1a). Successive records of PBs and their frequency fluctuations within a time window of ±0.5 day are shown in Fig. 1b and c. It should be noted that there is possibility that one PB is regarded as two events if one PB occurs just within the overlapping of two time windows at the same time which belong to two successive seismic events. However, this case is rarely occurred and would not introduce evident systematic errors.

3 Statistical similarity

The probability density function (PDF) of PBs frequency fluctuations within time window ±0.5 day, from $P(z_1)$ to $P(z_{100})$, collapses on nearly the same curve (Fig. 2a) and exhibits nearly symmetric behavior with a fat tail. Here, $z_{\Delta n}$ is rescaled ($z_{\Delta n} = Z_{\Delta n}/\sigma$) by the standard deviation. For comparison, we also present the PDF of PBs frequency fluctuations within time window ±4 days (Fig. 2b). It is clearly shown that the PDF is no longer symmetric around the center and deviates evidently from the former.

PBs frequency fluctuations for more time interval scales are also investigated. We find that the $P(z_{\Delta n})$ within time window ±0.5 day exhibits a common functional form for various time interval scales in the range $1 \le \Delta n \le 100$. When superimposed, all the data fall on nearly the same curve (Fig. 2c). The PDFs with more time interval scales within time window ±4 days are plotted in Fig. 2d.

The energy dissipated in an earthquake relates with the earthquake magnitude M. Figure 3a shows that the frequency distributions of earthquakes are power-law form $y \propto S^{-3.0}$ ($S \equiv \exp(M)$). The energy fluctuations for earthquakes are defined as

NHESSD
2, 3183–3192, 2014

$Z_{\Delta n} = S_{n+\Delta n} - S_n$ and their PDFs are plotted with $\Delta n = 1, 10$, and 100 (solid symbols) in Fig. 3b, respectively. The results show fat tails and non-Gaussian behavior. It is consistent with previously reported results both for the worldwide seismic catalog and the Northern California catalog (Caruso et al., 2007).

For comparison, we fit $P(S_1)$, $P(S_{10})$ and $P(S_{100})$ to a q-Gaussian distribution, referred as Tsallis statistics (Tsallis, 1988; Tsallis et al., 1998)

$$P(x) = [1 - \beta(1-q)x^2]^{\frac{1}{1-q}}, \tag{1}$$

where both β and q are parameters. For $q = 1$, Eq. (1) reduces to Gaussian distribution. As shown in Fig. 3b, a good agreement with q-Gaussian distribution may find for $q = 1.98$ (red line). In spite of local fluctuation, both PBs frequency fluctuations (open symbols) and corresponding earthquakes energy fluctuations (solid symbols) fall on nearly the same curve.

4 Conclusions

We found that the PDFs for PBs frequency fluctuations and corresponding earthquakes energy fluctuations share similar invariant structure of non-Gaussian form with fat tails. It is valid for very different time interval scales $1 \le \Delta n \le 100$. As for earthquakes energy fluctuations, their PDFs are consistent with previously reported results which are compatible with the fact that the occurrence of earthquakes is spatiotemporal correlated (Corral, 2004). Compared with Gaussian processes, the fat tails character of the distribution indicates that there are rare but relatively large magnitude fluctuations. Clusters of small fluctuations are connected by these rare but large magnitude fluctuations. Specially, this invariant structure for PBs frequency fluctuation is valid only within a relatively shorter time window ±0.5 day. This time window dependent behavior around earthquakes shows consistence with previously reported results. These results show that sharp variations of particle counting rates occur more frequently when approaching the earthquakes (Anagnostopoulos et al., 2012; Wang et al., 2012).

NHESSD
2, 3183–3192, 2014

In this paper we focused on universal statistical behavior both for PBs frequency fluctuations and earthquakes energy fluctuations. Furthermore, we emphasized the similarity of the PDFs between PBs frequency fluctuations and earthquakes energy fluctuations. Both their PDFs share the similar time scale invariance and exhibit symmetry around center with fat tails. The scaled PDFs for different time intervals Δn collapsed on nearly the same curve. However, this invariant character is time windows dependent and valid within ±0.5 day in contrast to ±4 days.

Acknowledgements. We thank the DEMETER and the CDPP (Centre de Données de la Physique des Plasmas) for providing of data. We would like to thank Yuqian Ma, Xiangcheng Meng, Hui Wang, Xinqiao Li, Feng Shi, Yanbing Xu, Zhenghua An, Wenqi Jiang, Xiaoxia Yu, Xiaoyun Zhao, Xin Li, Hainan Lin, Sai Wang and Dong Zhao for useful discussions. This work was supported in part by the National Natural Science Foundation of China under Grant No. 11075166 and 11375203.

References

Aleksandrin, S. Yu., Galper, A. M., Grishantzeva, L. A., Koldashov, S. V., Maslennikov, L. V., Murashov, A. M., Picozza, P., Sgrigna, V., and Voronov, S. A.: High-energy charged particle bursts in the near-Earth space as earthquake precursors, Ann. Geophys., 21, 597–602, doi:10.5194/angeo-21-597-2003, 2003. 3184

Anagnostopoulos, G. C., Vassiliadis, E., and Pulinets, S.: Characteristics of flux-time profiles, temporal evolution, and spatial distribution of radiation-belt electron precipitation bursts in the upper ionosphere before great and giant earthquakes, Ann. Geophys.-Italy, 55, 21–36, 2012. 3184, 3187

Caruso, F., Pluchino, A., Latora, V., Vinciguerra, S., and Rapisarda, A.: Analysis of self-organized criticality in the Olami–Feder–Christensen model and in real earthquakes, Phys. Rev. E, 75, 055101 1–4, 2007. 3187

Corral, Á.: Long-term clustering, scaling, and universality in the temporal occurrence of earthquakes, Phys. Rev. Lett., 92, 108501, 1–4, 2004. 3187

Fidani, C., Battiston, R., and Burger, W. J.: A study of the correlation between earthquakes and NOAA satellite energetic particle bursts, Remote Sens., 2, 2170–2184, 2010. 3184

Frohlich, C. and Davis, S. D.: Teleseismic *b* values; Or, much ado about 1.0, J. Geophys. Res., 98, 631–644, 1993. 3184

Galper, A. M., Koldashov, S. V., and Voronov, S. A.: High-energy particle flux variation as earthquake predictors, Adv. Space Res., 15, 131–134, 1995. 3184

Gutenberg, B. and Richter, C. F.: Frequency of earthquakes in California, B. Seismol. Soc. Am., 34, 185–188, 1944. 3184

Ishimoto, M. and Iida, K.: Observations of earthquakes registered with the microseismograph constructed recently, Bull. Earthquake Res. Inst., 17, 443–478, 1939. 3184

Kagan, Y. Y.: Universality of the seismic moment-frequency relation, Pure Appl. Geophys., 155, 537–573, 1999. 3185

Omori, F.: On the after-shocks of earthquakes, J. Coll. Sci., 7, 111–200, 1894. 3185

Sauvaud, J. A., Moreau, T., Maggiolo, R., Treilhou, J.-P., Jacquey, C., Cros, A., Coutelier, J., Rouzaud, J., Penou, E., and Gangloff, M.: High-energy electron detection onboard DEMETER: the IDP spectrometer, description and first results on the inner belt, Planet. Space Sci., 54, 502–511, 2006. 3185

Sgrigna, V., Carota, L., Conti, L., Corsi, M., Galper, A. M, Koldashov, S. V., Murashov, A. M., Picozza, P., Scrimaglio, R., and Stagni, L.: Correlations between earthquakes and anomalous particle bursts from SAMPEX/PET satellite observations, J. Atmos. Sol.-Terr. Phys., 67, 1448–1462, 2005. 3184

Sidiropoulos, N. F., Anagnostopoulos, G., and Rigas, V.: Comparative study on earthquake and ground based transmitter induced radiation belt electron precipitation at middle latitudes, Nat. Hazards Earth Syst. Sci., 11, 1901–1913, doi:10.5194/nhess-11-1901-2011, 2011. 3184

Tsallis, C.: Possible generalization of Boltzmann–Gibbs statistics, J. Stat. Phys., 52, 479–487, 1988. 3187

Tsallis, C., Mendes, R. S., and Plastino, A. R.: The role of constraints within generalized nonextensive statistics, Physica A, 261, 534–554, 1998. 3187

Utsu, T.: Aftershocks and earthquake statistics, III, Analyses of the distribution of earthquakes in magnitude, time, and space with special consideration to clustering characteristics of earthquake occurrence, J. Fac. Sci., Hokkaido Univ. Ser. VII, 3, 379–441, 1971. 3185

Wang, P., Wang, H., Lu, H., Meng, X., Zhong, J., Wang, H., Shi, F., Xu, Y., Li, X., Yu, X., Zhao, X., Wu, F., An, Z., Jiang, W., and Liu, H.: Common dependence on earthquake magnitudes for the trapped particles bursts approaching the earthquake, arXiv:1211.1796, 2012. 3184, 3187

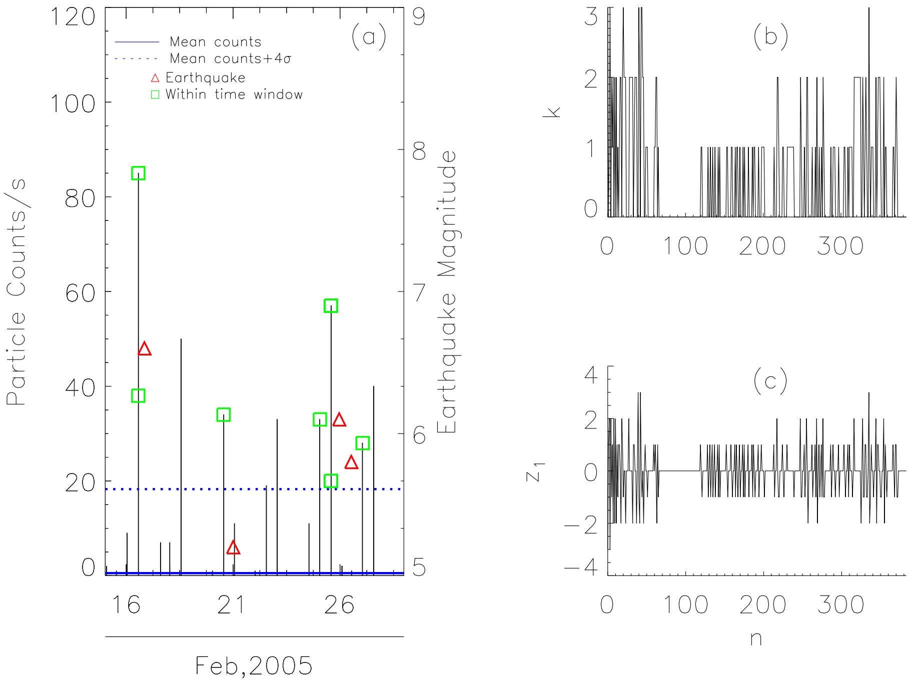

Fig. 1. Definition of PBs and their occurrence frequency fluctuations. **(a)** Typical trapped particles fluxes and seismic events from selected area and time range. The solid blue line is the average counts of background particles. The dotted blue line is the sum of the average counts and 4σ. The green squares are PBs within a time window ±1 day. Seismic events are represented by red triangles. **(b)** Number k_n (integer) of PBs occurrence frequency according to successive seismic events n. **(c)** Successive frequency fluctuation, $Z_1 = k_{n+1} - k_n$ obtained from the series shown in **(b)**.

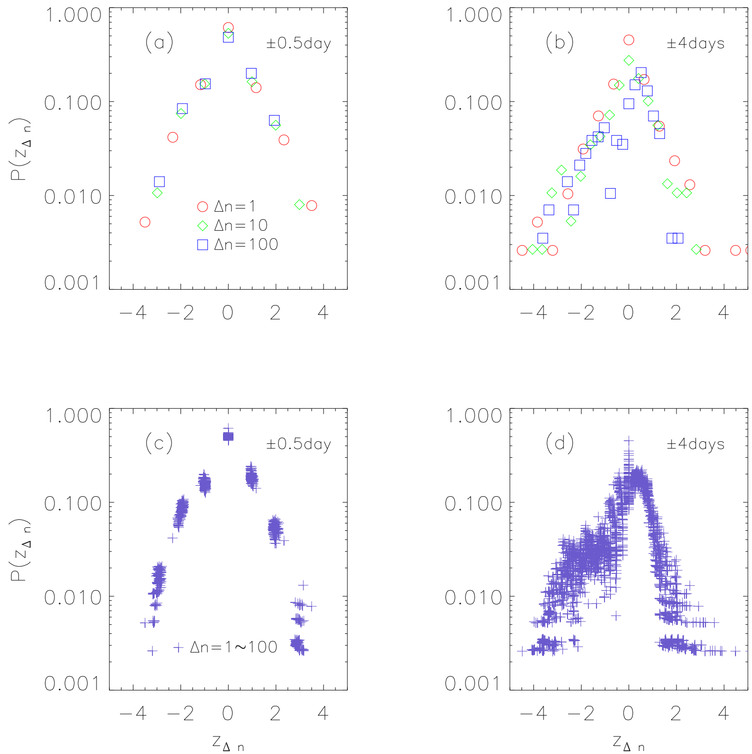

Fig. 2. Invariant structure of PBs frequency fluctuations. **(a)** The PDFs of PBs frequency fluctuations, $P(z_1)$, $P(z_{10})$ and $P(z_{100})$, for all records within a time window ±0.5 day. $z_{\Delta n} = Z_{\Delta n}/\sigma$, where σ is the standard deviation. **(b)** The PDFs of PBs frequency fluctuations, $P(z_1)$, $P(z_{10})$ and $P(z_{100})$, for all records within a time window ±4 days. **(c)** Superposition of $P(z_{\Delta n})$ at different time intervals within a time window ±0.5 day. **(d)** Superposition of $P(z_{\Delta n})$ at different time intervals within a time window ±4 days.

NHESSD
2, 3183–3192, 2014

Statistical similarity

P. Wang et al.

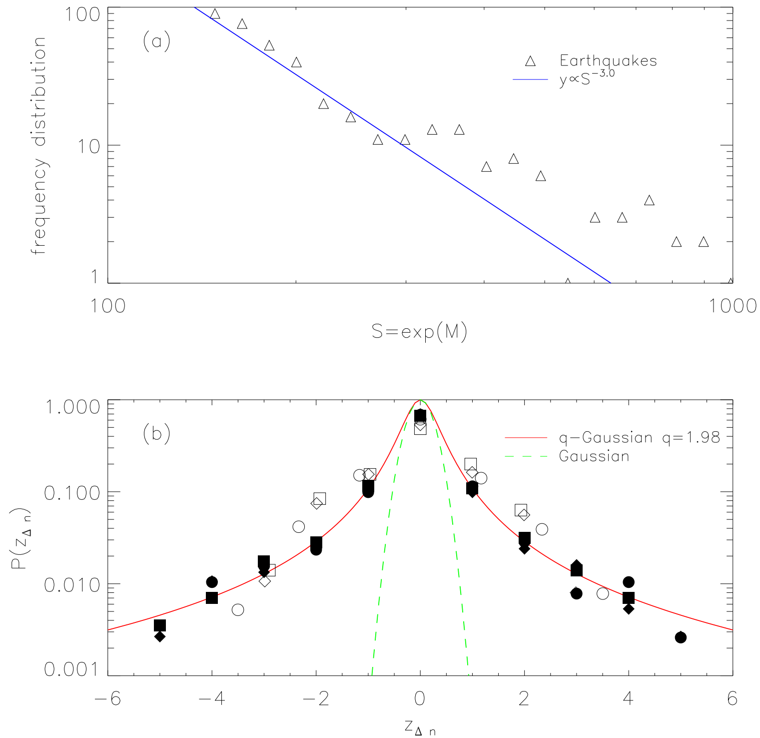

Fig. 3. Comparison of the PDFs for fluctuations of PBs occurrence frequency and energy dissipated in real earthquakes. **(a)** Power law distribution of energy dissipated in earthquakes. **(b)** Superposition of $P(z_{\Delta n})$ both for PBs (empty symbols) and earthquakes (solid symbols) at different time intervals. $\Delta n = 1, 10$ and 100, correspond to circles, diamonds and squares, respectively. The red line is given by the q-Gaussian distribution and a standard Gaussian distribution is plotted as a dashed green line.

NHESSD
2, 3183–3192, 2014