Evidence of Deterministic Components in the Apparent Randomness of GRBs: Clues of a Chaotic Dynamic

G. Greco[1], R. Bedogni[1], G. Beskin[2], M. Ciszak[3], S. Dichiara[4], A. Guarnieri[5], C. Guidorzi[4], S. Karpov[2], F. Marino[6], A. Ortolan[7], R. Rosa[8]

[1]INAF-Astronomical Observatory of Bologna, Italy,[2]Special Astrophysical Observatory of Russia Academy of Science, Russia ,[3]CNR-Istituto Nazionale di Ottica, Italy,[4]Physics Department, University of Ferrara, Italy [5]Department of Astronomy, University of Bologna, Italy , [6]CNR- Istituto dei Sistemi Complessi, Italy [7]NFN-Laboratori Nazionali di Legnaro, Italy, [8]Department of Statistical Science, University of Bologna, Italy

Correspondence and requests for materials contact: giuseppe.greco8@unibo.it

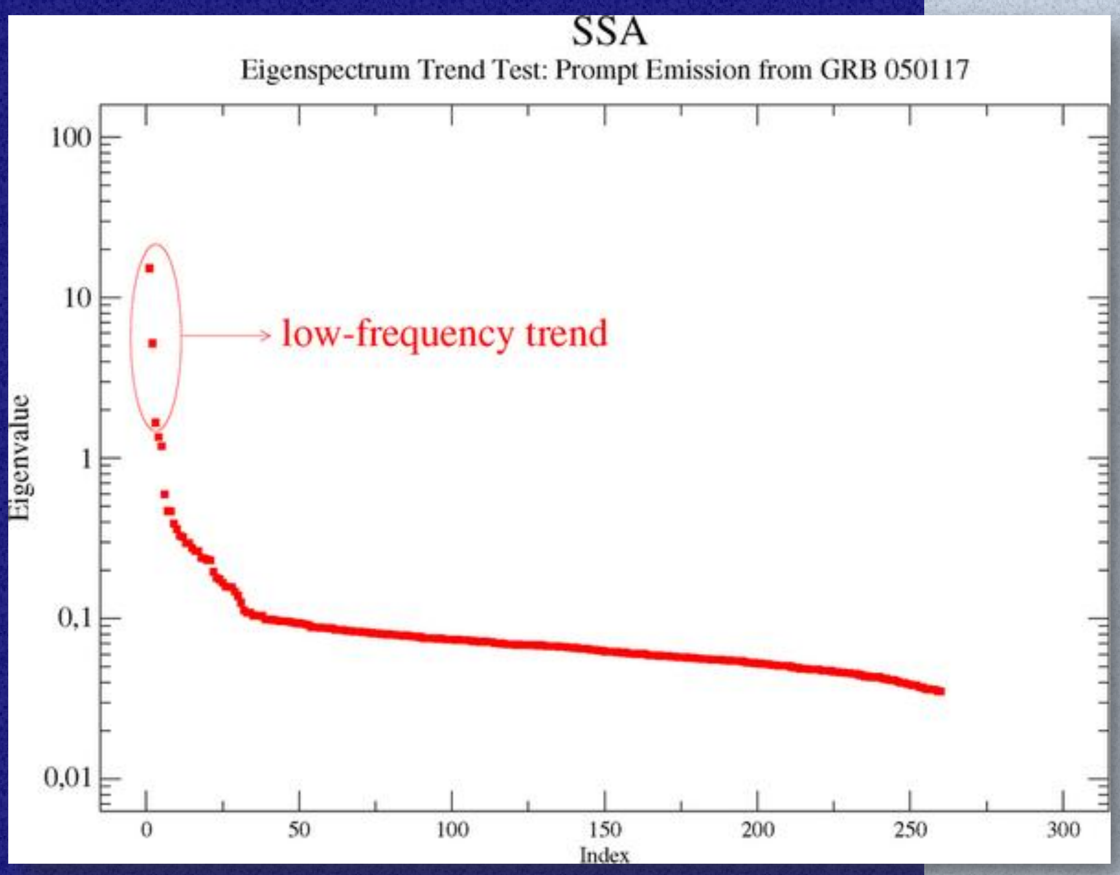

Fig 1: SSA Eigenspectrum of prompt emission from GRB 050117.

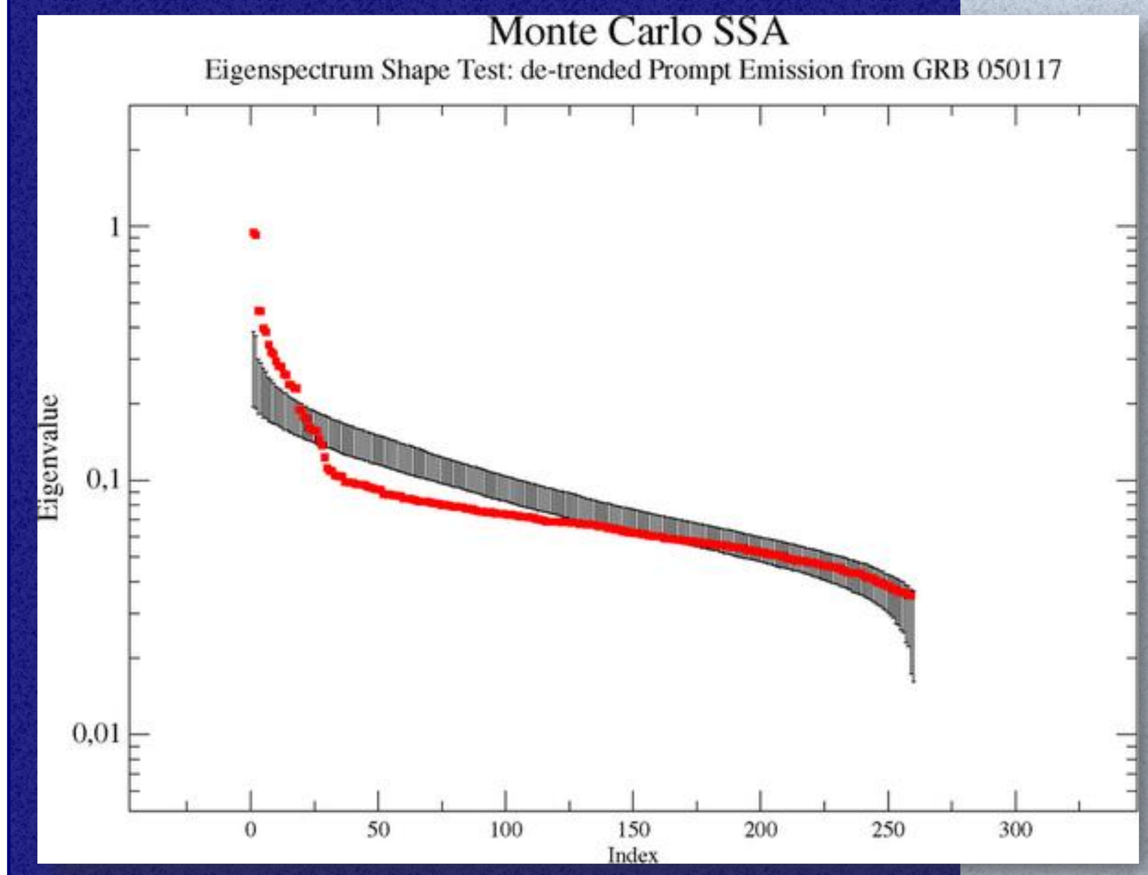

Fig. 2: Monte Carlo SSA Eigenspectrum of prompt emission from GRB050117 in which the low-frequency trend is subtracted.

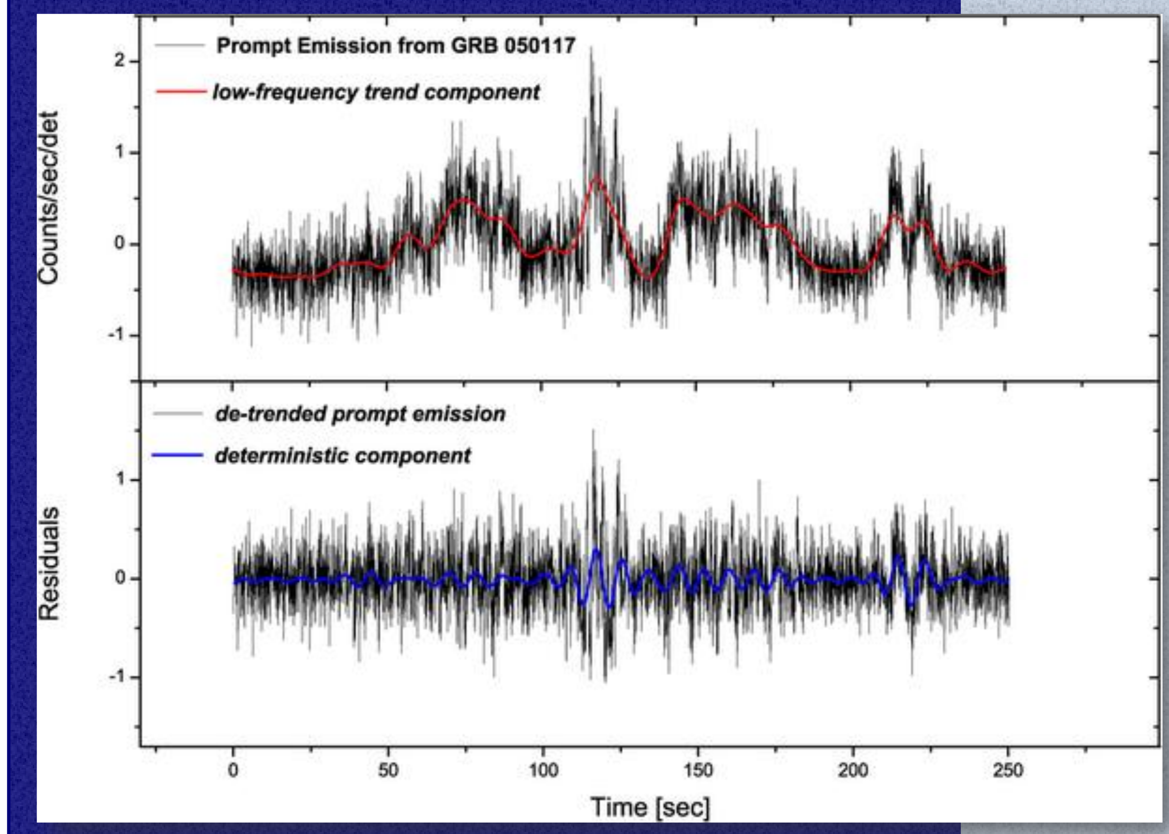

Fig. 3: SSA Reconstruction.

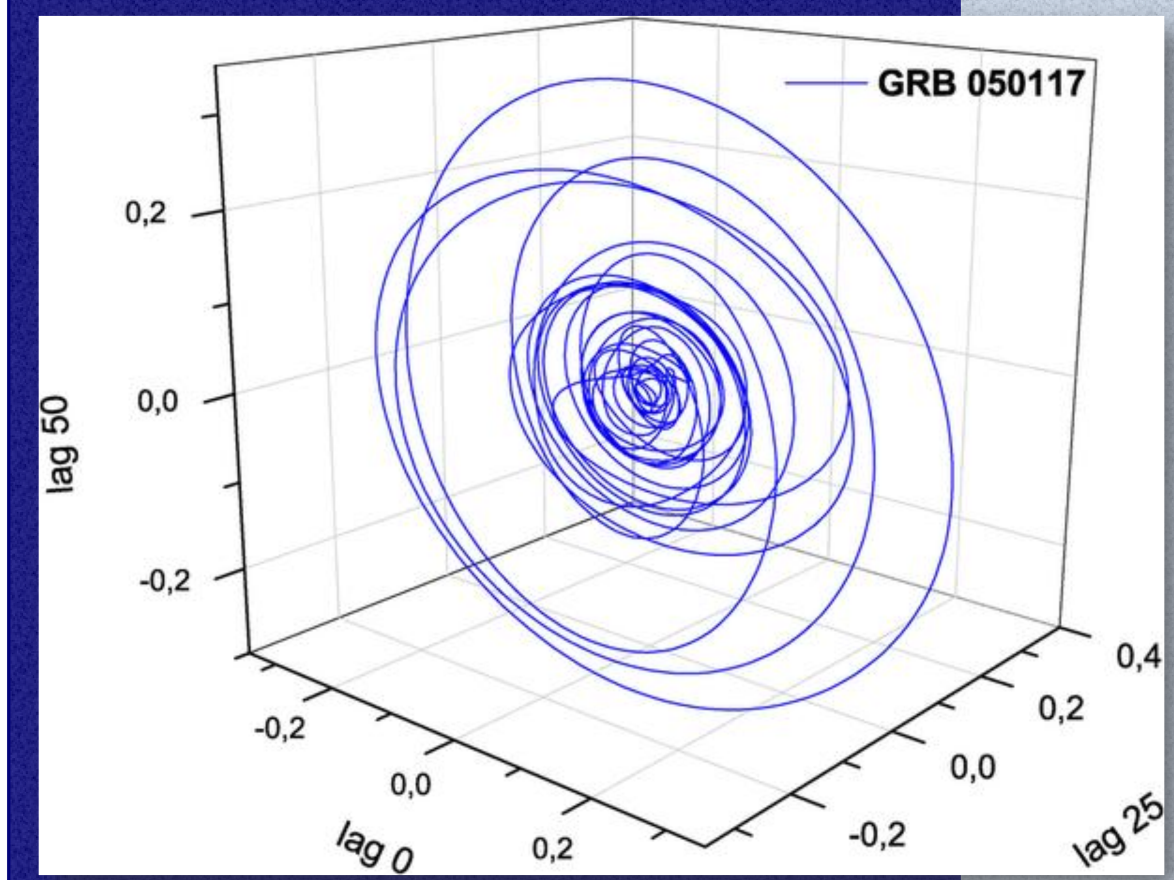

Fig. 4: Phase Space Portrait of the deterministic components discovered in the prompt emission from GRB 050117.

Introduction

This work aims to investigate the apparent randomness of the GRB time profiles making extensive use of nonlinear techniques combining the advanced spectral method of the Singular Spectrum Analysis (SSA) with the classical tools provided by the Chaos Theory. Despite their morphological complexity, we detect evidence of a non stochastic short-term variability during the overall burst duration – seemingly consistent with a chaotic behavior. The phase space portrait of such variability shows the existence of a well-defined strange attractor underlying the erratic prompt emission structures. We present the analysis of GRB 050117 detected by Swift satellite (*Greco et al., 2011*)

Methods

The Singular Spectrum Analysis (SSA, *Golyandina, Nekrutkin, and Zhigljavsky, 2001*) belongs to the class of methods which use orthogonal functions, allegedly more efficient because calculated on the basis of data rather than on the basis of a fixed selected base as in Fourier and Wavelet Transforms. Indeed, this property makes the SSA a very effective statistical method in the decomposition of the original time series into a defined number of independent and interpretable components. It permits to separate signal from noise even if the Signal-to-Noise level varies when recording the original time series – a typical feature of GRBs' prompt emissions. At all time in this research project, a Monte Carlo SSA (*Ghil et al. 2002*) test was used to distinguish between genuine deterministic components and components generated by a pure red-noise process. Red-noise is known to be significantly relevant in several natural systems. When dealing with red-noise, a first-order autoregressive process is usually considered: *AR(1)*, given by $x_t = \varphi x_{t-1} + \varepsilon_t$ with $0<\varphi<1$ and ε_t independent identically distributed normal errors. Using the Monte Carlo SSA test, we estimated the parameters of the *AR(1)* model starting from the very same time series, and using a maximum-likelihood criterion. For instance, if an eigenvalue λ_L lies outside a 99% noise percentile, then the red-noise null hypothesis can be rejected with this confidence. Otherwise, that particular SSA component of the time series cannot be considered as significantly different from red-noise. The shape of the so-called SSA Eingespectrum is analyzed to identify possible evidence of deterministic activity in the prompt emission from GRBs selected in our sample. The SSA Eingespectrum plot shows the eigenvalue, λ_L, ranked by order that provides the variance of the time series in the direction specified by the corresponding eigenvector $\boldsymbol{E_L}$. Each eigenvalue represents the fraction of total variance explained by the associated component. By selecting low-frequency SSA components, we can identify nonlinear slow trends. In this work, Kendall's τ nonparametric trend tests are performed to identify those components that are significantly non-stationary over the length of the time series at 99% confidence levels (**Fig. 1**). Once the eigenvalues identifying the trend have been determined, the de-trended prompt light curve is to be tested against the null-hypothesis, H_0: the variability nature of the data are consistent with a pure *AR(1)* random noise. We found that the first eigenvalues are dominant and lie outside the intervals that define a purely stochastic behavior. Furthermore, we were able to reject the null hypothesis at the 0.01 level, as the variances showed to be significantly different from the noise-variance. The results of this analysis are showed in **Fig. 2**. In **Fig. 3** can be observed the detailed steps of the SSA reconstruction process. As evidenced, a deterministic signal clearly emerges out of a significant fraction of random walk noise, from the time of the original signal to the end of this analysis.

Conclusion

The use of the advanced spectral method of the SSA, together with the classical tools provided for in the Theory of Chaos, proved largely successful in the analysis of the complex morphological structure of the prompt emissions from GRBs. Despite the extremely complicated and random profile of the prompt γ-ray signals, we found a well-defined strange attractor (**Fig. 4**) **.** This implies that the nature of the prompt time variability is not purely stochastic. Rather, similar inherent physical processes appear to take place during the entire dynamic evolution of GRB explosions. Evidence was found of a fractal ($D_2 \approx 2.4$) and chaotic nature ($\lambda_{max} = 0.0089 \pm 0.0007$of the GRB attractors). Ongoing analysis show the same dynamics in the satellite database of BeppoSax, Fermi and BATSE.

References:

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