6th Asia-Pacific Conference on Plasma Physics, 9-14 Oct, 2022, Remote e-conference

Complexity approaches to space plasma dynamics

Juan Alejandro Valdivia[1,2], Benjamin Toledo[1,2], Jose Rogan[1,2], Sylvain Blunier[1], R.A. Miranda[3], P. R. Munoz[4], A.C.-L. Chian[5,6]
[1]Departamento de Fisica, Facultad de Ciencias, Universidad de Chile, Chile
[2]Center of the Development of Nanoscience and Nanotechnology, Chile
[3]UnB-Gama Campus and Institute of Physics, University of Brasília, Brazil
[4]School of Mathematical Sciences, University of Adelaide, Australia
[5]National Institute for Space Research (INPE), Brazil
[6]Department of Physics and Astronomy, University of La Serena, Chile
e-mail (speaker): alejo@uchile.cl

In space physics we are usually dealing with high dimensional and nonlinear complex systems, in which it is common to try to construct reduced physical or data derived descriptions of their evolution. As a particular example, the magnetosphere is a high dimensional system that is driven by a high dimension turbulent solar wind, and as a result it produces a complex system, composed of a set of subsystems that are coupled by electromagnetic and plasma waves displaying diverse complex behavior ranging from turbulent and laminar flows, particle beams, anisotropic pressure gradients, magnetic reconnection, dipolarization fronts, among many others [Borovsky and Valdivia, 2018]. However, despite the scientific successes in understanding these processes during the last years, there are a number of open questions that remain to be solved [Borovsky et al., 2020].

It is important to note that these systems are in general **dissipative systems**, so that the reduced physical or data derived models of their evolution intends to describe the behavior of the system close to a "driven attractor" of a much **lower dimension**. Here, machine learning descriptions (e.g., simple or deep neural networks) have become quite popular in the last few years. However, understanding the nature of the inherent fluctuations that these high dimension systems display must be undertaken, for they provide and indication of the subjacent errors of the models, and can always feed back through the nonlinearity and high dimensionality of the system to produce unexpected dynamics, particularly, when they systems is driven as is the case of the magnetosphere. This behavior is at the heart of complex systems that display complex behavior, coherent structures, multifractality, etc., topics that can be analyzed with new and exciting techniques.

For example, there are a number of studies that have shown that some of the turbulent solar wind and magnetospheric variables display multifractal behavior. To analyze such systems, new and interesting techniques based on information and multifractal measures have been developed. For example, we have constructed a complexity plane to study the magnetic fluctuation anisotropy in reconnection exhausts (Miranda et al., 2021). Similarly, we have analyzed the multifractality strength in spatial patterns of magnetospheric fluctuations close to the Earth surface (Toledo et al., 2022). The results must have consequences for our understanding of the physical processes that participate in the system's evolution.

Furthermore, the existence of these magnetic fluctuations in the solar wind and magnetosphere, being multifractal or not, have consequences for the construction of reliable models and forecasts of space weather, requiring ways to handle these fluctuations that are inherent in such high dimensional systems, something that has not been achieved so far. Here we show how it is possible to construct a Nonlinear System Science description, based on artificial intelligence techniques, that takes into consideration the existence of these fluctuations to ascertain which are the robust variables that such a model should have and estimate the expected fluctuation levels in the system. We have applied this strategy to the solarwind-magnetosphere system (Blunier et al., 2021). Although, there has been quite a lot of advances in these topics during the last decades, the are a number of issues that remain open and deserve attention [Borovsky et al., 2020].

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