Complexity Heliophysics

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Heliophysics in Europe and 1st European Heliophysics Community meeting
19–21 November 2024 ONLINE

Complex Systems Methods for Geospace Research (*SSRv* 2023)

Space Science Reviews (2023) 219:38
https://doi.org/10.1007/s11214-023-00979-7

Complex Systems Methods Characterizing Nonlinear Processes in the Near-Earth Electromagnetic Environment: Recent Advances and Open Challenges

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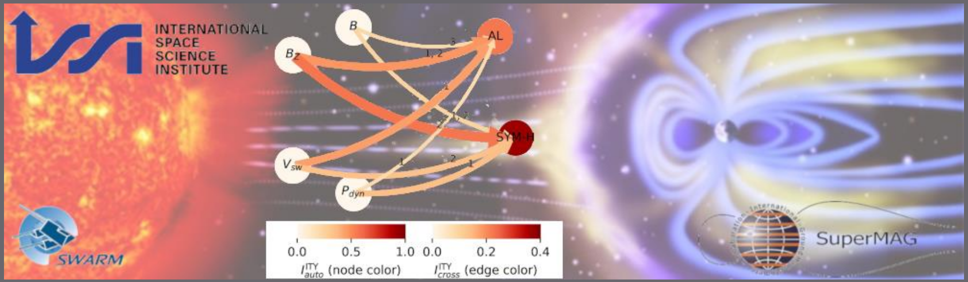
Received: 3 November 2022 / Accepted: 25 May 2023 / Published online: 12 July 2023

Abstract
Learning from successful applications of methods originating in statistical mechanics, complex systems science, or information theory in one scientific field (e.g., atmospheric physics or climatology) can provide important insights or conceptual ideas for other areas (e.g., space sciences) or even stimulate new research questions and approaches. For instance, quantification and attribution of dynamical complexity in output time series of nonlinear dynamical systems is a key challenge across scientific disciplines. Especially in the field of space physics, an early and accurate detection of characteristic dissimilarity between normal and abnormal states (e.g., pre-storm activity vs. magnetic storms) has the potential to vastly improve space weather diagnosis and, consequently, the mitigation of space weather hazards.

This review provides a systematic overview on existing nonlinear dynamical systems-based methodologies along with key results of their previous applications in a space physics context, which particularly illustrates how complementary modern complex systems approaches have recently shaped our understanding of nonlinear magnetospheric variability. The rising number of corresponding studies demonstrates that the multiplicity of nonlinear time series analysis methods developed during the last decades offers great potentials for uncovering relevant yet complex processes interlinking different geospace subsystems, variables and spatiotemporal scales.

Keywords Solar wind – magnetosphere – ionosphere coupling · Magnetic storms · Magnetospheric substorms · Space weather · Nonlinear dynamics · Complex systems

ISSI International Team (2019-2022)



https://www.issibern.ch/teams/nearearthelecenvi/

Complex systems perspectives pertaining to the research of the near-Earth electromagnetic environment

- This a largely interdisciplinary International Team, combining expertise from both space physics and nonlinear physics communities, which had been selected for funding by the International Space Science Institute (ISSI) in 2019.

- Taken together, the multiplicity of recently developed approaches in the field of nonlinear time series analysis offers great potentials for uncovering relevant yet complex processes interlinking different geospace subsystems, variables and spatio-temporal scales.

- The Team aims to provide a first-time systematic assessment of these techniques and their applicability in the context of geomagnetic variability.

Complexity Heliophysics: Living Reviews (*SSRv* 2024)

Space Science Reviews (2024) 220:52
https://doi.org/10.1007/s11214-024-01081-2

Complexity Heliophysics: A Lived and Living History of Systems and Complexity Science in Heliophysics

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Received: 16 June 2023 / Accepted: 21 May 2024 / Published online: 4 July 2024

Abstract
This review examines *complexity science* in the context of Heliophysics, describing it not as a discipline, but as a paradigm. In the context of Heliophysics, complexity science is the study of a star, interplanetary environment, magnetosphere, upper and terrestrial atmospheres, and planetary surface as interacting subsystems. Complexity science studies entities in a system (e.g., electrons in an atom, planets in a solar system, individuals in a society) and their interactions, and is the nature of what emerges from these interactions. It is a paradigm that employs systems approaches and is inherently multi- and cross-scale. Heliophysics processes span at least 15 orders of magnitude in space and another 15 in time, and its reaches go well beyond our own solar system and Earth's space environment to touch planetary, exoplanetary, and astrophysical domains. It is an uncommon domain within which to explore complexity science. After first outlining the dimensions of complexity science, the review proceeds in three epochal parts: 1) A pivotal year in the Complexity Heliophysics paradigm: 1996; 2) The transitional years that established foundations of the paradigm (1996-2010); and 3) The emergent literature largely beyond 2010. This review article excavates the lived and living history of complexity science in Heliophysics. It identifies five dimensions of complexity science, some enjoying much scholarship in Heliophysics, others that represent relative gaps in the existing research. The history reveals a grand challenge that confronts Heliophysics, as with most physical sciences, to understand the research intersection between fundamental science (e.g., complexity science) and applied science (e.g., artificial intelligence and machine learning (AI/ML)). A risk science framework is suggested as a way of formulating the grand scientific and societal challenges in a way that AI/ML and complexity science converge. The intention is to provide inspiration, help researchers think more coherently about ideas of complexity science in Heliophysics, and guide future research. It will be instructive to Heliophysics researchers, but also to any reader interested in or hoping to advance the frontier of systems and complexity science.

Keywords Complexity science · Systems science · Data science · Machine learning · Dynamical systems · Transdisciplinary · Networks · Heliophysics · Resilience · Convergence · Philosophy of science · Emergence · Epistemology

Complexity Heliophysics: A lived and living history of systems and complexity science in Heliophysics [McGranaghan; 2024]
https://tinyurl.com/mcgranaghan-CH

Five Organizing Dimensions

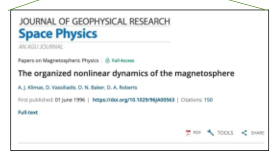
Manual Review 400

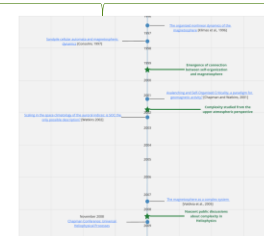
Natural Language Processing Review 4000

- Emergence, self-organization, and scaling theory
- Systems science and crossing scales
- Information and uncertainty quantification
- Risk science and resilience
- Networks, network science, and collective behavior

History

1996: epochal year — *1996-2010: transitional years* — *Emerging* — *Grand Opportunity*


JOURNAL OF GEOPHYSICAL RESEARCH
Space Physics
AN AGU JOURNAL
Papers on Magnetospheric Physics | Full Access
The organized nonlinear dynamics of the magnetosphere
A. J. Klimas, D. Vassiliadis, D. N. Baker, D. A. Roberts
First published: 01 June 1996 | https://doi.org/10.1029/96JA00563 | Citations: 150
Full text



Opportunities

There is an important intersection between complexity and AI

A ‘risk science’ framework can be a layer where fundamental understanding and predictive capability converge

These challenges are not only technical, but cultural, too

Recent example: scientific discovery in RB dynamics through causality analysis

AGU ADVANCING EARTH AND SPACE SCIENCES

Geophysical Research Letters

RESEARCH LETTER
10.1029/2023GL107166

Causal Inference in the Outer Radiation Belt: Evidence for Local Acceleration

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P. Manshour and C. Papadimitriou contributed equally to this work.

Key Points:

- Evidence of direct causality from relativistic into ultra-relativistic electrons, compatible with local acceleration in the outer belt
- Detection of information transfer unveils the mechanisms of energy transfer in radiation belts, important for space weather forecasting
- Information flow formulation of causality has a great potential for space physics discoveries

Supporting Information:

Supporting Information may be found in the online version of this article.

Abstract Currently, there is no clear understanding of the comprehensive set of variables that controls fluxes of relativistic electrons within the outer radiation belt. Herein, the methodology based on causal inference is applied for identification of factors that control fluxes of relativistic electrons in the outer belt. The patterns of interactions between the solar wind, geomagnetic activity and belt electrons have been investigated. We found a significant information transfer from solar wind, geomagnetic activity and fluxes of very low energy electrons (54 keV), into fluxes of relativistic (470 keV) and ultra-relativistic (2.23 MeV) electrons. We present evidence of a direct causal relationship from relativistic into ultra-relativistic electrons, which points to a local acceleration mechanism for electrons energization. It is demonstrated that the observed information transfer from low energy electrons at 54 keV into energetic electrons at 470 keV is due to the presence of common external drivers such as substorm activity.

Information Theory and Machine Learning for Geospace Research, (Wing & Balasis, *ASR* 2024)

- Information theory can be integrated with machine learning to achieve greater insights and performance.

- Information theory can help untangle, prune, and select the input parameters for machine learning based modeling by identifying and ranking the relevant parameters that actually transfer information to the model output parameters.

- As a result, it can help reduce the dimensionality of the networks, shorten the training time, and improve the model accuracies.

RB Neural Network Model Assisted with Information Theory

ADVANCING EARTH AND SPACE SCIENCE

Space Weather

RESEARCH ARTICLE

10.1029/2022SW003090

Key Points:

- An empirical model to predict state of radiation belt relativistic electrons is developed
- The model prediction efficiency increases with increasing L^* with a PE > 0.6 at $L^* > 5$
- The model can potentially complement a class of empirical models that input observations from low earth orbit

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Citation:

Wing, S., Turner, D. L., Ukhorskiy, A. Y., Johnson, J. R., Sotirelis, T., Nikoukar, R., & Romeo, G. (2022). Modeling radiation belt electrons with information theory informed neural networks. *Space Weather*, *20*, e2022SW003090. https://doi.org/10.1029/2022SW003090

Modeling Radiation Belt Electrons With Information Theory Informed Neural Networks

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Abstract An empirical model of radiation belt relativistic electrons (μ = 560–875 MeV G^{-1} and I = 0.088–0.14 R_E $G^{0.5}$) with average energy ~1.3 MeV is developed. The model inputs solar wind parameters (velocity, density, interplanetary magnetic field (IMF) |B|, *Bz*, and *By*), magnetospheric state parameters (SYM-H and AL), and L^*. The model outputs the radiation belt electron phase space density (PSD). The model is operational from $L^* = 3$ to 6.5. The model is constructed with neural networks assisted by information theory. Information theory is used to select the most effective and relevant solar wind and magnetospheric input parameters plus their lag times based on their information transfer to the PSD. Based on the test set, the model prediction efficiency (PE) increases with increasing L^*, ranging from –0.043 at $L^* = 3$ to 0.76 at $L^* = 6.5$. The model PE is near 0 at $L^* = 3$–4 because at this L^* range, the solar wind and magnetospheric parameters transfer little information to the PSD. Using solar wind observations at L1 and magnetospheric index (AL and SYM-H) models solely driven by solar wind, the radiation belt model can be used to forecast PSD 30–60 min ahead. This baseline model can potentially complement a class of empirical models that input data from low earth orbit (LEO).