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Complexity Heliophysics: A [new] system science that transcends the previous boundaries of our field

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Synopsis

1. **The 21st century is the time of complexity. We delineate it and its importance as necessary to solve 'wicked problems.'**
2. **Inherently transdisciplinary, trans-scale, and interconnected to living systems, the solution to Heliophysics' identity crisis and to unlock the next generation of scientific discovery may be to embrace complexity.**
3. **With the right foresight, direction, and incentive over the next ten years, Heliophysics can become a beacon for how all of society thinks about and does complexity science.**

> The [21st] century will be the century of complexity. -Stephen Hawking

Why did Hawking say this? Let's take a moment to consider the historical position. From the Enlightenment to the dawn of the 20th century, humankind answered one fundamental question about the universe after another. To name a few: Newton's laws of motion and his law of universal gravitation laid out in *Principia* [1], Laplace's celestial mechanical description of the solar system [2], and understanding of electricity, magnetism, and optics. Then, in a scientific blink of an eye, a cascade of revolutions disrupted our knowledge of the universe. Most notably punctuated by Einstein's *annus mirabilis* in 1905, in which he published four papers that revolutionized understanding of the fundamental concepts of space, time, mass, and energy, the ensuing decades witnessed similar revolutions in philosophy (Ludwig Wittgenstein's *Tractatus Logico-Philosophicus* explored the limits of science) and mathematics (Kurt Gödel's incompleteness theorem stated that in any reasonable mathematical system there will always be true statements that cannot be proven). Each revolution gestured toward knowledge that was outside of the current system of thought or study, and each led to profound new understanding of our universe. We suggest that thinking outside of the current system is the complex systems approach and that similar progress is possible in Heliophysics if we embrace it.

1 What is complexity?

Those who have been around complexity for any period of time have heard the interminable attempts to define it. Part of the reason for its obstinacy to definition is that the terms of traditional science are ill-equipped for that description. Yet grappling with a definition teaches something new each time, so we'll attempt an introduction here. A working definition is that complexity is a property of a system that has many parts which interact nonlinearly to produce behavior that is more than simply the sum of those parts—emergent behavior. Rather than pin down a definition, complexity is better understood by outlining it. Complexity might have the following characteristics:

- Self-organization: The idea that order at some higher or coarse-grained level of a system is organized by a number of interacting sub-systems.
- Fractal structure: multiple scales of structure exist, often self-similar and nested.
- Open, nonlinear, feedback: Complex systems are open and responsive to external perturbations, behave nonlinearly in response to those perturbations, and use feedback loops to mediate those responses. Donella Meadows writes, “The concept of feedback opens up the idea that a system can cause its own behavior.” [3]. Indeed, it is feedback that gives rise to regularities that become the focus of complexity science methods, “It is the consistent behavior pattern over a long period of time that is the first hint of the existence of a feedback loop.”
- Networked: The elements of a complex system are linked together through certain relationships and the graph, or network, is a representation that is capable of describing complexity;
- Collectivity and Emergence: the collective behavior of the system is unexpected, different than, or not immediately predictable from the aggregation of the behavior of the individual parts; it is said to emerge from the interacting parts [4].

Despite the lack of easy and consensus definition, the science of studying complexity, complexity science, is a rigorous domain. Complexity science is the study of phenomena that emerge from a collection of interacting objects [5]. It is a science of:

- Statistics and computation;
- Power laws;
- Information theory (including uncertainty quantification);
- Graph/Network science; and
- Feedback loops.

A shared characteristic of these elements of complexity science is an attempt to negotiate across scales and to find representations that can accommodate the movement among scales. This is acutely important to the next decade of Heliophysics, when cross-scale and multiscale science will be central. A final element we will add to complexity science is the discovery of coarse-grained[1] representations of systems that are useful to understanding and specification (e.g., effective theories).

[1] `https://www.edge.org/response-detail/27162`

Yet, as Gödel's incompleteness theorem tells us, no formal system can completely and unambiguously describe a system. So, complexity also involves methods to address the strangeness of real systems such as game theory, agent-based modeling, and data visualization.

We believe that complexity science has been a part of some of our most profound scientific advances and we may now be entering an age when it is a requirement to make progress on our grand challenges. The questions we are now asking have outstripped the methods of traditional, reductionist, disciplinary science. These questions abound across disciplines: What computations occur in a neuronal population that produce cognitive activity? How do food webs give rise to an ecology? What determines the path and intensity of a hurricane? How does information spread across a social network? What factors dictate the risk and resiliency of the power grid? How do genotype and phenotype interact to determine response to a disease? What is the swarm intelligence of a beehive? What factors control the emergence of active regions on the Sun? It is not difficult to come up with others.

The important point is that the methods that were effective to the questions we asked before the 1900s no longer serve this new landscape.

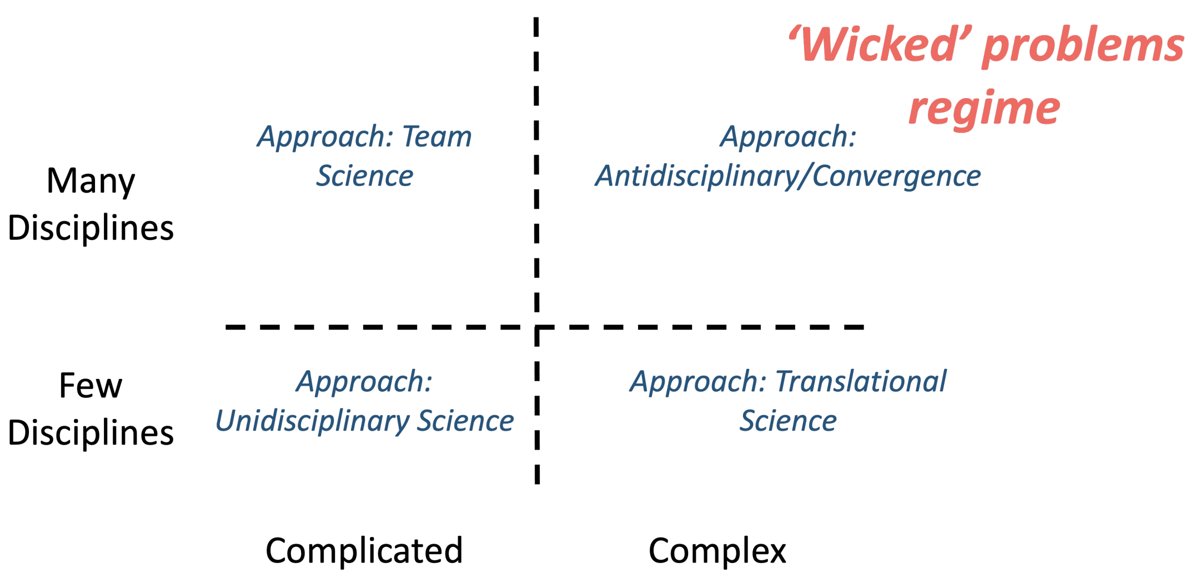

Figure 1: An illlustration of the problemscape and approaches of solar and space physics. *reproduced from [5]*

We, society not just scientists, require a new paradigm built from complexity. No response to that existential challenge yet exists in part because sciences cling to disciplines. President of the trailblazing complexity science institution, the Santa Fe Institute[2], writes:

> . . . we retreat into disciplinarity, a comfortable and familiar zone of tribal and historical

[2]https://www.santafe.edu/

> cohesiveness, where the consolation of crowds helps to justify our activities. . . The cost of this maneuver is that it restricts the scope of our inquiries and causes us to lose sight of the numerous extradisciplinary ideas and methods that have contributed to (and will be required to further) our progress through the thorny branches of science. - David Krakauer [6]

Why is Heliophysics positioned to be a complexity science?

Heliophysics processes span at least 15 orders of magnitude in space and another 15 in time. The processes we study reach beyond what is traditionally defined as Heliophysics, including not only our own solar system and Earth space environment but also planetary, exoplanetary, and astrophysical domains. Indeed, the demands on Heliophysics science are growing exponentially. In addition to requiring fundamental contribution to 'sister disciplines,' Heliophysics now must also address the human impact–e.g., the risk of space weather and humanity's physical expansion into space.

- Heliophysics inherently crosses disciplines. Heliophysics is combinatorial, encompassing threads of science separated by artificial boundaries of funding and academic labels [7]. Overcoming the boundaries requires a triumvirate of approaches: coupled models, statistical inference, and the properties of complexity [8, 9].
- Heliophysics makes crossing scales not a cutting-edge aspect of research as it might be in Earth Science or Planetary Science, but a prerequisite to progress at all. Magnetospheric physics seems to be coming up to a limit that requires embedding kinetic scale physics into macro-scale simulations (e.g., [10]).
- Heliophysics is a fundamental science that inextricably also contains human activity. It is the science of potential creation, sustaining, and destruction of life [Cohen et al., 2022][3]. Space weather already encompasses the response of society to Heliophysical phenomena, but Heliophysics naturally requires the integration of any organism's response to stellar and astrophysical activity. There is a reason that biologists and ecologists have been at the forefront of complexity science and that is because living systems cannot deny complexity, they have had to confront it. "The greatest challenge today, not just in cell biology and ecology but in all of science, is the accurate and complete description of complex systems. [11].

The history of Heliophysics has, like many sciences, been one of specialization–categorizing and separating domains and building understanding within those ever more boundaried systems. The approach has produced remarkable achievement, yet in a century in which sensing and analysis capabilities are revealing not only the complexity of Heliophysics phenomena but also enabling

[3] `http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/623127/6920789/19-15ae97d7b3d301b7bfbb20b84331470f_CohenIanJ3.pdf`

more comprehensive study of that complexity, we face both an exciting opportunity and an important imperative to shift the paradigm [12]–the advent of Complexity Heliophysics.

We argue that, with the right foresight, direction, and incentive over the next ten years, Heliophysics can revolutionize how we do complexity science, becoming a beacon for all of society to make these changes in how we see the world. This may be a response to what has been called Heliophysics' "existential crisis" [Cohen et al., 2022][4].

2 Complexity science in Heliophysics: Trailblazers

There has been steady, albeit relatively niche, research in Heliophysics that treats the solar-terrestrial connection as a complex system. [13] review the study of the magnetosphere as a dynamical system while [14] review self-organized criticality in solar and astrophysics, as two resources that provide excellent introductions. [15] recognized the trend toward systems and complexity in the geospace sciences and synthesized a bold vision for the Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) community.

We note that trailblazers are not only individuals, but institutions and more collective groups. NASA and the National Science Foundation have both made strides in directions important to cultivating Complexity Heliophysics–emphasizing Team Science (e.g., the NSF's Convergence Accelerator Program[5] and NASA's DRIVE Science Centers) and specific solicitations for data-driven methods (e.g., the NSF's Harnessing the Data Revolution Program[6]).

We do not attempt to be comprehensive with our review of complexity science within Heliophysics in this paper, which is the focus of a forthcoming living reviews article

Development of communities have accompanied these advances in research, creating the capacity for complexity science in Heliophysics.

3 Risk and resilience framework

Heliophysics science in the coming decade must also address the existential threats to society and life that are posed by the interaction between a planet and its star. For Earth this is known as space weather. We briefly describe a framework, defined by elements and approaches of complexity science, for studying the risks due to solar and space physics.

We need a framework that encompasses much of the existing research and follows the lead communities like ecology and biology who are more mature in complexity science have pioneered: a risk and resilience framework. A resilient system is one that can accommodate changes and reorganize itself while maintaining the crucial attributes that give the system its unique characteristics [16]. Figure 2 is a high-level representation of what a risk and resilience approach might look like for Heliophysics, emphasizing our own solar-terrestrial system.

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[4] http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/623127/6920789/19-15ae97d7b3d301b7bfbb20b84331470f_CohenIanJ3.pdf

[5] https://beta.nsf.gov/funding/initiatives/convergence-accelerator

[6] https://www.nsf.gov/cise/harnessingdata/

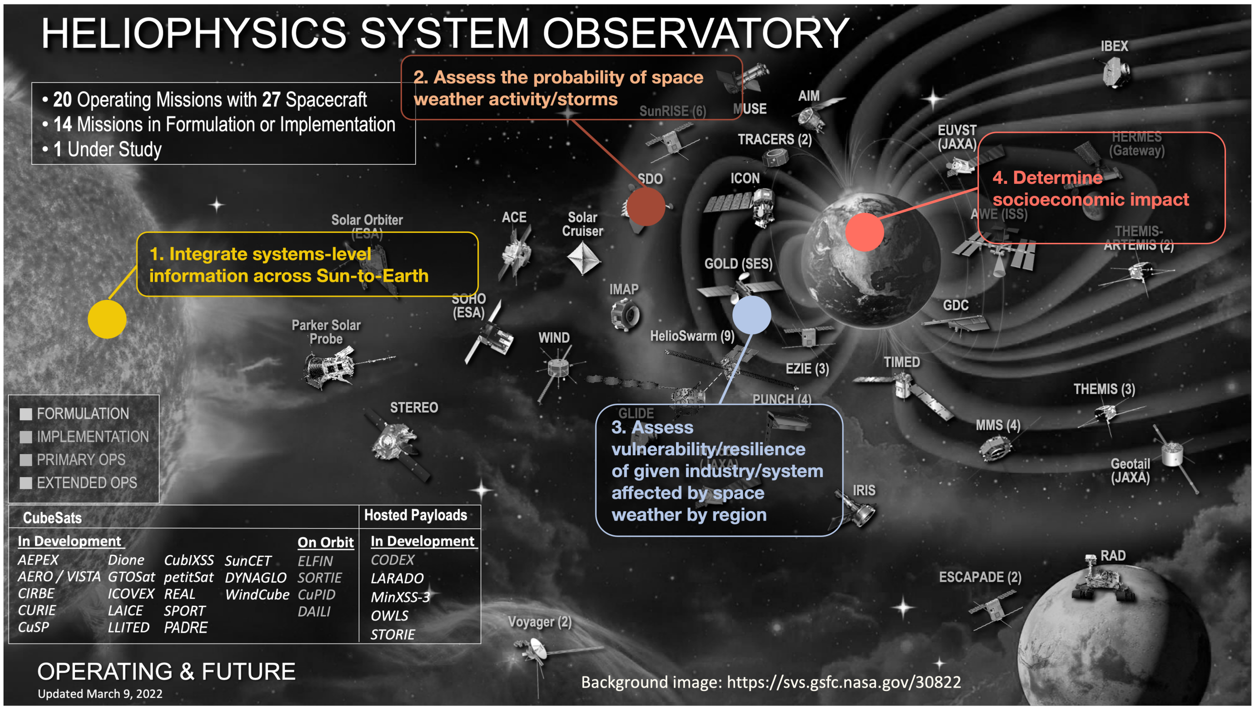

Figure 2: High-level risk and resilience framework for the solar-terrestrial system.

The risk and resiliency framework achieves numerous needs: treats Heliophysics as a system, connects the science to living systems and societal impact, invokes concepts of dynamical stability, and places risks from Heliophysical phenomena on a common ground with other risks that are convolved (for instance, climate where the Sixth Intergovernmental Panel on Climate Change (IPCC)[7] addressed resilience directly, "Resilience. . . describes not just the ability to maintain essential function, identity and structure, but also the capacity for transformation.")

Complexity science offers a means to do science and engineering for resilient systems [16].

4 The way forward: Recommendations

- Define and support adoption of a risk and resiliency framework that can guide adoption of complexity science methods in solar and space physics. This includes systems science thinking and tools for the concomitant data integration, connecting Heliophysics phenomena to space weather risks (and in the future, risks to life on any planet) along with their likelihoods, and translating our science to societal impacts.

- Design programs that support systems research in Heliophysics and specifically articulate the use of complexity science methods such as network science and power law distributions

[7]https://www.ipcc.ch/report/ar6/wg2/

- Consider how to move toward fuller inclusion of systems-level information with the design of new analysis methods, metrics and indices (e.g., new proxies of geomagnetic activity), and missions.

- Foster partnerships between Heliophysics communities and complex systems institutes like the Santa Fe Institute and the MIT Media Laboratory's Space Exploration Initiative. These places are now beginning to recognize the complexity of the space environment and these are conversations our researchers should be helping to shape.

- Value skills of facilitation, gathering, and Team Science [17]. Complexity defies disciplines, so the teams required to do complexity science must be radically transdisciplinary. Figure 1 above indicates that a complex response to wicked problems requires anti-disciplinarity. Note that we do not use the term to mean 'against' disciplines, but increased plurality of thought and transdisciplinary connections. [18] outline concrete paths to improve the science of Team Science [19] in Heliophysics, which include: Make Team Science and balanced team formation an important evaluation criteria in proposals and educate reviewers on the importance of Team Science in eliminating status-quo-enabling networks thus increasing the scientific breakthrough potential of proposals; Support Communities of Practice (CoP) for Heliophysics that provide new linkages and produce capable processes and technologies to use the knowledge and thus enhance knowledge transfer and innovation in every discipline; and Actively support diversity, equity, and inclusion (DEI) and support underrepresented members of our community (i.e., embrace plurality of thought). The following recommendation builds on an aspect of team science that bridges DEI and plurality of thought.

- Federal agencies need to further support for DEI: Plurality of thought does not automatically follow from improving representation of historically underrepresented groups. We must be deliberate in supporting all voices in Heliophysics science and in growing plurality in those conversations. Access to and success in Heliophysics (indeed all science, technology, engineering, and math (STEM) areas) seems in the current system to be largely the result of years of accumulated differential gains that add up to privilege. To see improvement in Heliophysics Team Science requires improvement in DEI, which requires improvement in grade school education, which requires overcoming socioeconomic, racial, and gender barriers. Overcoming these barriers may occur on longer-than-decadal timescales, but we must invest in conversations and support that can seed those changes in this decade (important examples include; better availability of childcare and better access to early childhood education).

- Explore the relationship between complexity and AI: There is a grand challenge and ongoing conversation between understanding and prediction. Physics attempts to create narratives, theories, and explanations of our world while the advent of an age of high-dimensional, complex ('big') data has been accompanied by algorithms with increasing predictive power, but that remain opaque to interpretation. In society, this takes the form of physics-based science vs. artificial intelligence/machine learning (AI/ML). Indeed, this separation has even been called a 'schism' in science [20]. In Heliophysics, this is in part represented by the research vs. operations (fundamental science vs. application-oriented science) tension. We should be exploring the liminal space between these dichotomies and promote research (through funding and recognition) that palpates these spaces. They might define the future of our science and make Heliophysics a community at the cutting-edge.

Help Heliophysics continue to foster a complexity science paradigm.

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References

[1] Isaac Newton, Andrew Motte, and N. W Chittenden. *Newton's Principia. The mathematical principles of natural philosophy*. 1848.

[2] Laplace Pierre Simon. *A Treatise of Celestial Mechanics*. 1798.

[3] Donella Meadows. *Thinking in Systems*. 2015.

[4] Leo Torres, Ann Sizemore Blevins, Danielle S. Bassett, and Tina Eliassi-Rad. The why, how, and when of representations for complex systems. *SIAM Rev.*, 63:435–485, 2021.

[5] Ryan Mcgranaghan. The evolution of heliophysics: Complexity, community, and open science. *Frontiers in Astronomy and Space Sciences*, 2022.

[6] D.C. Krakauer. *Worlds Hidden in Plain Sight*. SFI Press, 2019.

[7] Madhulika Guhathakurta. Too big to solve? heliophysics pioneers a new approach to intractable problems. *Space Weather*, 15:12 – 13, 2017.

[8] Ryan M. McGranaghan, Asti Bhatt, Tomoko Matsuo, Anthony J. Mannucci, Joshua L. Semeter, and Seebany Datta-Barua. Ushering in a new frontier in geospace through data science. *Journal of Geophysical Research: Space Physics*, 122(12):12,586–12,590, 2017.

[9] Ryan Mcgranaghan, Joseph E. Borovsky, and Michael H. Denton. How do we accomplish system science in space? *Eos*, 2018.

[10] Kareem A. Sorathia, Aleksandr Y. Ukhorskiy, Viacheslav G. Merkin, Joseph F. Fennell, and Seth G. Claudepierre. Modeling the depletion and recovery of the outer radiation belt during a geomagnetic storm: Combined mhd and test particle simulations. *Journal of Geophysical Research: Space Physics*, 123:5590 – 5609, 2018.

[11] Edward O. Wilson. *Consilience: The Unity of Knowledge*. 1998.

[12] Thomas S. Kuhn. *The Structure of Scientific Revolutions*. 1962.

[13] A. J. Klimas, D. Vassiliadis, D. N. Baker, and D. A. Roberts. The organized nonlinear dynamics of the magnetosphere. *Journal of Geophysical Research: Space Physics*, 101(A6):13089–13113, 1996.

[14] Markus J. Aschwanden, Norma B. Crosby, Michaila Dimitropoulou, Manolis K. Georgoulis, Stefan Hergarten, James McAteer, Alexander V. Milovanov, Shin Mineshige, Laura Morales, Naoto Nishizuka, and et al. 25 years of self-organized criticality: Solar and astrophysics. *Space Science Reviews*, 198(1-4):47–166, 2014.

[15] Jeffrey Thayer and Steering Committee. Cedar strategic vision – the new dimension. 2010.

[16] Marten Scheffer. *Critical Transitions in Nature and Society*. 2009.

[17] R. McGranaghan, A. Kellerman, and M. Olson. Communities must learn to join forces to tackle grand challenges. *Eos*, 2022.

[18] Ryan McGranaghan, Barbara Thompson, and Alexa Halford. The science of team science and inclusivity in heliophysics. *Heliophysics 2050*, 2020.

[19] National Research Council. *Enhancing the Effectiveness of Team Science*. The National Academies Press, Washington, DC, 2015.

[20] David Krakauer. At the limits of thought. *Aeon*, 2020.