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The evolution of heliophysics: Complexity, community, and open science

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Responding to the grand challenges that confront the Earth and Space Sciences requires an embrace of methods from the field of complexity and systems science that can adapt our thinking and our science to be more inter- and cross-disciplinary and enable broader connection across individuals, teams, communities, and sciences. Culturally, as scientifically, broader disciplinary approaches are imperative. The cultural challenge is the disconnect that exists between groups. These disconnects preclude plurality in discussions, harm creativity and innovation, and give rise to a palpable malaise, especially at the early career stage. Together, the scientific and cultural grand challenges we describe point to a need for a new set of literacies and curriculum that the advent of open science supports–increased cross-disciplinarity, team science that generates community connections, plurality and inclusion in our science and in how we connect.

KEYWORDS

data science, information science, complexity, heliophysics, epistemology, philosophy of science, open science, commons

Introduction

At 2 a.m. on February 15, the Electric Reliability Council of Texas (ERCOT) declared an Energy Alert Level 3 and utilities began rotating outages due to high consumer demand. The heightened alert was the result of unusual, though perhaps not unexpected, cold temperatures and unpredictable power consumption behavior of individuals and businesses–together causing ERCOT officials to nervously watch the frequency of the electric power grid drop outside of the narrow 60 Hz band, a number affected by innumerable moving pieces and dynamics from the weather to the operation of the power grid to the user demand on the system. The events of February 2021 reawakened the world to the precarity of the power grid, a massively complex and integrated system whose resilience in the face of the variability of the natural and human world is anything but guaranteed. The way we see and attempt to control the grid is like trying to know everything about a room we are not standing in when all we have is a temperature reading from a thermometer within it.

The grid is at the whim of the natural world and the vicissitudes of human behavior, a truly complex system (Meadows and Wright, 2008). The interconnected power grid is merely an especially visible example of the complexity of the world that we attempt to

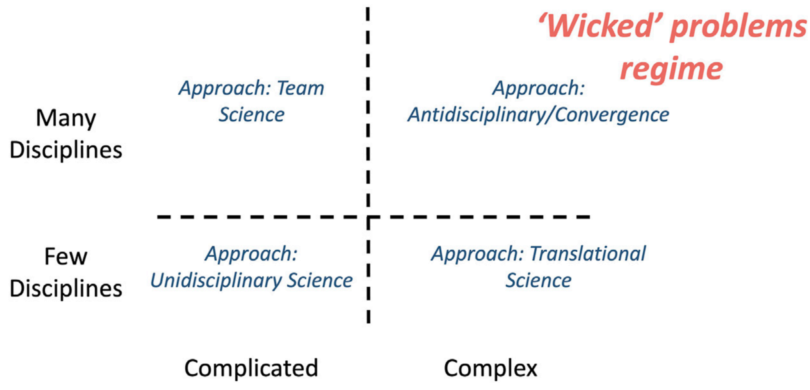

FIGURE 1
An illlustration of the problemscape and approaches of the Earth and Space Sciences.

understand. We realize that we face a new challenge in the Earth and Space Sciences. While the paradigm of reducing problems to separate sub-disciplines to study as distinct constituent parts has produced remarkable insights, all scientists are confronted with interconnected problems of increasing existential importance and yet have been obstinate to progress.

Our world is interconnected. John Muir wrote, "When we try to pick out anything by itself, we find it hitched to everything else in the Universe." (Muir and Gleason, 1911) As these interconnections become more important to the problems we are trying to solve, the whole becomes more than the sum of the parts–or in other words, the system is complex and exhibits emergent behavior. Figure 1 illustrates the situation. A given problem can be graded over four quadrants detailing the number of disciplines and whether the problem is complicated or complex (Kurtz and Snowden, 2003; Kurtz and Snowden, 2007). We use complicated to refer to hard problems that can be addressed by reduction to rules or processes. Alternatively, complexity refers to phenomena that emerge from a collection of interacting objects. The term 'emergence' is important in that it describes how the phenomena is not present in any of the interacting parts alone and cannot be reduced in the same manner as complicated problems (more below in *Introduction*). For problems involving few disciplines and complicated behavior (lower left quadrant), unidisciplinary approaches are effective. As more disciplines are required where the system behavior remains complicated rather than complex (upper left quadrant), the approach is one of team science (Council, 2015) where the most important advance required is improved collaboration, coordination, and communication. In the lower right quadrant, behavior is complex but perhaps can be addressed with a relatively few disciplines the approach is translational, or amenable to borrowing methods of complexity science across those few disciplines. The upper right quadrant requires many disciplines and the system exhibits complex behavior. This is the 'wicked problems regime.' The approach to wicked problems must be *antidisciplinary* or convergent, where we must merge innovative ideas, approaches, and technologies from a wide and diverse range of sectors and expertise. Note here that I define antidisciplinary as increased plurality of thought and transdisciplinary connections. It does *not* mean against disciplines. A better metaphor might be that antimatter as a partner to ordinary matter. This is the problem landscape of the Earth and Space Sciences. New approaches are needed when we cross the thresholds into the wicked problems regime. An increasing number of our problems land in this upper right regime.

Improving the resiliency of the power grid in the face of compounding human-natural forces is one of these wicked problems and a part of a class of them in our society (e.g., global pandemics, climate change). Indeed, problems are often elevated to this regime when human behavior is tied in. I suggest that to respond to the wicked problems in the Earth and Space Sciences requires methods from the field of complexity science, expanded or new literacies that we need to develop as individuals and incentivize as a community, and open science as an emerging framework for these changes and to make them sustainable and scalable.

> We have reached a stage where the pace of discovery and the nature of shared knowledge bring the whole venerable exercise of disciplinary fads into question . . . The cost of [disciplinarity] 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 (Krakauer, 2019)

The cultural reach

Coupled to the scientific challenges are cultural ones. There is a growing disconnect between individuals, whether within Heliophysics or between Heliophysicists and Earth Scientists (or even between Heliophysicists and artists and designers). That disconnect is linked to a malaise among the communities of scientists and engineers in the Earth and Space Sciences. This lack of fulfillment has been attributed to a lack of connection, diversity, inclusivity, and a general feeling of fatigue (McGranaghan et al., 2020). Though no cross-sections of Earth and Space Science are immune to the effects, it is perhaps the early career community that experiences it most acutely (Evans et al., 2018; Bankston, 2021) as growing connections is particularly important to their work and lives.

In the scientific as in the cultural, perhaps the solution is through interconnections. I propose, based on professional experiences and many personal conversations and observations, that much of this cultural malaise is because of the now-undeniable recognition that our disciplinary approaches, the strictures of our thinking, no longer describe the reality that we are faced with–in the scientific sense as in the cultural. Our disciplinary silos cannot describe the scientific problems we witness, which depend on the interconnections, just as in our communities the ways we segment and separate ourselves deny richer interactions and relationality. In the early career community, perhaps, this feeling is particularly acute.

Our challenge may be indicative of a broader cultural problem: a disconnect between scientists and the public. Perhaps born of different expectations of literacies between the scientist and the citizen (e.g., critical skepticism and hypothesis testing), the disconnect can lead to distrust of science. Below we outline new literacies we need to address issues across the Heliophysics community, but we should also consider those that will allow us to reach across the scientific community to the public.

The complex response

We need to revitalize our vision for the field. The goal of this piece is to clarify and reveal the nature of the problems facing the Earth and Space Sciences to enable conversations about solutions to them. I have chosen to ground it in the concept of complexity because of its ability to deal with interconnections. We define complexity and relate it specifically to the field of Heliophysics, revitalizing it in the process. We also describe the implications of complexity–the degree of collaboration that it requires and the philosophy that will underlie our efforts to reach it. Though it is contextualized in Heliophysics, the discourse is relevant to all areas of science.

Our development will lead us to a new vision and a remaking of Heliophysics, one with a broader scope and more open and cohesive community. We describe the practices we need to adopt and the literacies/capacities we need to create in our workforce to achieve frontier scientific discovery at the pace and complexity that society needs. We suggest new metrics we need to consider that drive resources and policy for a more flourishing community and science. We use the concept of *Open Science* (Vicente-Saez and Martinez-Fuentes, 2018) as a portmanteau to encompass the cultural implications of this shift in philosophy.

This commentary comes from an early career perspective. It is an introduction to a new way of thinking about Heliophysics that can connect the sub-disciplines in our science, our science to other sciences, and the society of Earth and Space Scientists–creating a healthier community. It is also an attempt to let that perspective create a map to tangible, actionable recommendations and be a basis for new comprehensive solutions. In T*he complex response* below I offer suggestions that may help our community focus in new ways: new metrics, literacies and capacities we need to value and build, and a curriculum that encompasses them.

Complexity and heliophysics

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

Complexity science is the study of phenomena that emerge from a collection of interacting objects. To understand a complex system requires a plurality of frameworks and we must be able to move between levels (e.g., micro and macro). As such, complexity science spans numerous dimensions. 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. Each of these subsystems can be further broken down into regions (e.g., the auroral region of the upper atmosphere) and all the way down to more elementary components such as electrons and protons. Complexity science is a paradigm that suggests ways of reconciling the micro and macro scales. It is the collection of methods to understand a system across scales, the smaller scale behavior in connection with the larger-scale phenomena that emerge from it. The complex systems paradigm transcends the concepts of scale and discipline, providing methods to connect across them (Thayer, 2011). To evolve toward a complexity paradigm in Heliophysics requires understanding and adopting the methods of complexity. In the process of envisioning this transformation, other fields provide examples and inspiration: biology (Kauffman and Kauffman, 1993), ecology (Wilson, 1999), cognitive science (Varela et al., 1992), to name a few.

The methods of complexity

There are numerous methods that undergird complexity science. We only highlight a select few that have basis in

Heliophysics research already and can be foundations on which to build. The research cited below is not comprehensive, but meant to be a way into these topics for members of our community and those of other communities to find commonality.

Self-organization, emergence, and scaling theory Emergence is the term used to describe phenomena that are 'more than the sum of their parts' (Rosas et al., 2020). Emergence is observed in virtually all areas of inquiry, such as how large numbers of individual fish are able to behave dynamically as a school when threatened by a predator (Parrish et al., 2002). In terms of scale, emergence is the occurrence of actions at one scale giving rise to a phenomenon on another level. The idea that order at some higher dimension, or coarse-grained level of a system, is organized by a number of interacting sub-systems is called self-organization. Self-organization is a powerful toehold in complexity science because it reveals that emergence is observable in statistical characteristics of the system. If there are underlying driving mechanisms that are identical at all scales, a statistical signature is created that is consistent across scales–a power law (West, 2017). Emergence is a way that order is extracted from many interacting parts and power laws describe that order statistically. Self-organization and power law relationships have produced cross-system Heliophysics understanding for decades (e.g., (Consolini, 2002; Chang et al., 2003; Aschwanden et al., 2014; Budaev et al., 2015)). Though self-organization and scaling laws may be relatively new terms for many, the concept of developing an effective theory from coarse-grained principles is well understood to all scientists. Temperature is an average of all of the particles' motions in a gas, and is a better predictor of the system's future at a certain macro-level. Coarse-graining is how we model the behavior of a complex system without specifying every underlying cause and component that lead to system-level changes.

Information theory To analyze order mathematically, the driving principle of the complexity paradigm, one must begin with information and its counterpart, entropy. Information quantifies the amount of dependency or connection between a random variable and itself at a different time or with other variables at the same or different times. Entropy quantifies the amount of micro-states involved in the value of a random variable. Information theory provides rigorous mathematical formalisms to study the nonlinear relationships and feedbacks that characterize complex systems (Thayer, 2011), especially because they can go beyond linear correlational analyses, capture nonlinear relationships, and establish causalities. Entropy-based information theory is already a valuable tool in Heliophysics to determine the information flow among cross-system parameters, infer potential causalities, untangle the drivers, and provide observational constraints that can help guide the development of the theories and physics-based models (Wing and Johnson, 2019).

Network Science If the complexity science paradigm is about understanding the emergence of patterns from the interactions of their parts, then networks are its specimens and network science its toolkit. A network is simply a collection of entities, or nodes, and their relationships, or edges. For example, in a social network the nodes are people and the edges are the relationships with one another. As the network structure is remarkably representative of the natural world (Kauffman and Kauffman, 1993), thinking of a system in this way can lead to new and useful insights for Heliophysics (Dods et al., 2015; McGranaghan et al., 2017b; Hughes et al., 2022).

Resilience framework New frameworks are required to handle uncertainty and embody the complexity paradigm. A framework of resilience acknowledges complexity, taking into account the holistic system, and the probabilistic nature of complexity science. In this framework, a system is treated as complex and can be defined by whether or not it can accommodate changes and reorganize itself while maintaining the crucial attributes that give the system its unique characteristics (Scheffer et al., 2001). In Heliophysics a resilience framework involves two important principles: 1) considering the Sun-to-society system; and 2) quantifying uncertainty that arises from coarse-graining and statistical simplification. Heliophysics, with its societal implications (Schrijver et al., 2015), requires a resilience framework in order to translate the science of Heliophysics into actionable knowledge for space weather. Resilience offers a way that decisions can be made based on complex systems understanding.

Literacies, curriculum, and metrics for Complexity Heliophysics

Complexity Heliophysics requires our community to develop new literacies and the curriculum that encompasses them.

New capacities and literacies

The literacies are both technical and cultural. The methods of complexity science listed above reveal important technical competencies: scaling relationships, information theory, and network science (and the computational techniques required by them). Several others are less explicit in the development so far.

Data science Data science refers to scalable architectural approaches, techniques, software and algorithms which alter the paradigm by which data are collected, managed and analyzed and communicated. For years, our understanding of complex systems has benefited from taking advantage of comprehensive data-intensive approaches (McGranaghan et al., 2017a). Those skills for state-of-the-art data-driven sciences and technologies are even more important in light of the need to synthesize more encompassing disciplinary information for Heliophysics-related science. Knowledge engineering, or the skill of building the technologies that represent our knowledge, is emerging as an important sub-component of a data science literacy. Building better knowledge representation systems is a cornerstone of any approach to identify where information asymmetries and bottlenecks exist, recognize the whole of an individual's, group's, or project's contributions, and create information needed to design more productive incentive structures for our community.

Gathering and organizing The dramatic increase in the scale and complexity of scientific research required to address wicked problems must be reflected in the scale and diversity of our collaborations. A seldom-recognized skill in managing collaboration and fostering knowledge generation that now becomes incumbent upon all researchers is the ability to effectively bring larger groups together and cultivate effective connections across them (Council, 2015). We do not appropriately recognize and value the challenge and importance of the ability to create a cohesive and broad gathering. The importance of a leader's gathering, organization, and facilitation skills will be elevated. Indeed, these skills are central to improving diversity, equity, inclusivity, and accessibility (DEIA).

Resilience Martin Scheffer (Scheffer et al., 2001) defines a resilient system as one that can accommodate changes and reorganize itself while maintaining the crucial attributes that give the system its unique characteristics. It is the ability of an entity–e.g., asset, organization, community, region–to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance. It is clear that the researcher of today must adapt to more rapidly changing conditions, as the late Buckminster Fuller termed the pace of the appearance of ideas–accelerating acceleration. The resilient researcher is one prepared and equipped to respond to quickly changing conditions and capable of continual learning and reinvention of their frameworks.

Trans-media communication Knowledge is created and consumed in myriad new ways in the 21st century. While technical journal publication remains a primary outlet for the dissemination of scientific knowledge, to reach broader audiences and widen the impact of science in society researchers must embrace and become skilled in communicating across mediums, including blogs and newsletters, audio (e.g., podcasts), video (e.g., YouTube), and interactive data visualization.

It will be the job of all Heliophysicists to figure out how to develop these literacies. The list of jobs and responsibilities for Heliophysicists seems overly burdensome and it is not difficult to see why early career researchers feel overwhelmed. Perhaps not all skills need to be tackled by all Heliophysicists. Instead, infrastructure of various types (e.g., in the ability to construct more capable teams) can assist in meeting 21st century needs. We need to offset the burdensome nature of too much expectation on the individual and facilitate more collective activity and intelligence, which we describe in *New capacities and literacies* below.

Metrics of the future

To cultivate new literacies requires rethinking the visible quantities that our community uses to drive resources, particularly our most precious one: attention. These visible quantities are our metrics. Like exploring an unlit room with a flashlight, our understanding and the ways we choose to move depend on what we shine the light on. We need to rethink our metrics to incentivize the complexity paradigm and the more connected, healthier community it can create. This has been written about in the context of evaluating our models (Liemohn et al., 2018; Hietala et al., 2020; Morley, 2020; McGranaghan et al., 2021b)and those comments are important, but we also need new metrics that describe healthier community.

The call to our whole community is to think about what might be metrics for a future Heliophysics community. For all of our metrics, we must more carefully define what is being illuminated and what is being neglected. These new metrics should be matched to the literacies listed above, which are in turn derived from the tenets of complexity science. For instance, to incentivize the skill of gathering, we should value conference and workshop organization and better assess the success of such events. Complexity science suggest that the use of network measures can be used to assess the density of collaborative networks and diffusion of ideas and techniques and therefore to provide insight into the success of gathering. For trans-media communication we can value dissemination beyond just technical publications. Already we are beginning to recognize open source software contributions. Elevating that emphasis will promote better knowledge engineering capacities. Overall, these new metrics can become measures of success and feedback tools to understand and improve connectivity, communication, and collaboration in our community.

A curriculum for complexity heliophysics and a more healthy community: open science

These literacies can coalesce into a new curriculum–a more information-literate Heliophysics community. This must be done together through co-creation; I believe that open science is an ethos under which we can join these literacies. There are many defintions of open science, but the one that I think best captures our needs is:

> Open science is transparent and accessible knowledge that is shared and developed through collaborative networks. (Vicente-Saez and Martinez-Fuentes, 2018)

There are two distinct components of the definition, pointing to substantive directions that our field needs to progress. The first (*transparent and accessible knowledge*) alludes to the need for intelligent and accessible data infrastructure and the platform to use it. The second (*collaborative networks*) subtly identifies a grand challenge that confronts our field and our community: the need to imagine and construct participatory ecosystems of knowledge sharing, governance, and trust. Together these two components indicate a *Knowledge Commons* (McGranaghan et al., 2021a).

> I argue that the commons is what we need to build Complexity Heliophysics and a healthier community.

Knowledge commons

A knowledge commons is a combination of intelligent information representation and the openness, governance, and trust required to create a participatory ecosystem whereby the whole community maintains and evolves this shared information space (McGranaghan et al., 2021a). It is one structure for bringing together transdisciplinary knowledge, both explicit in the form of datasets and publications and tacit in the form of the knowledge held by individuals. The commons elevate data to knowledge through the FAIR data principles (Findable, Accessible, Interoperable, and Reusable) (Wilkinson et al., 2016). Co-creation and maintenance also promotes a healthier more connected community in much the same way that a community functions around shared farmland or pastures.

A knowledge commons is a solution to another problem that we must quickly address: the haphazard or irresponsible use of AI/ML. Semantically enriching our data facilitates integrating data and tracing the provenance of data. Making open and accessible the process followed to create and train the model and the source code of the subsequently produced model would improve our ability to interrogate it and broaden participation in the evaluation. The result would be more robust AI/ML models that are able to be built on rather than isolated and opaque that remain only within the researcher's mind (and sometimes pass even from there). Thus, the KCs support robustness and resiliency of our research artifacts (over brittleness) and collective improvement over silo'ed individual development.

The KCs have the potential to democratize access to information, knowledge, and one another in the Earth and Space Science community.

The implications for early career researchers are immense. The KCs raise awareness about the resources (people, capabilities, assets, contents, data, models) available–awareness that newcomers to the field, inordinately, are working to develop. Further, the KCs are a place for dissemination of research artifacts that may not fit into the traditional publishing model (e.g., data analysis pipelines), leading to greater visibility and credit across the full research process. Finally, the commons are a place for richer engagement, providing opportunities for connection outside of in-person conferences and events, which may not be well-suited to all researchers and, worse, can sometimes reinforce existing cliques to the detriment of inclusivity. Asymmetries in knowledge lead to unhealthy communities, and the knowledge commons offer a framework to overcome the asymmetries.

Conclusion

Our world is increasingly interconnected. Society's most pressing problems dictate a new ability to contend with the interconnections. We suggest that a complexity science philosophy–the approaches for understanding phenomena that emerge from a collection of interacting objects–is required. We have outlined the methods of *Complexity Heliophysics* and discussed the implications of the complexity mindset. Those implications include a healthier and more flourishing community that is better connected, a set of literacies that our community should cultivate, and new metrics that those driving resources might adopt. We coalesced these ideas under the emerging approaches of Open Science and the knowledge commons. Ultimately, we suggest that it may be time for our project groups, departments, and research institutes to embrace the full implications of a shift in philosophy toward complexity and to incentivize new literacies through a redesign of curricula and adoption of open science principles that might create a more flourishing science and community.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material further inquiries can be directed to the corresponding author.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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Conflict of interest

R. McGranaghan was employed by Orion Space Solutions LLC.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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