Agile Collaboration: Citizen Science as a Transdisciplinary Approach to Heliophysics

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Synopsis

Citizen science connects scientists with the public to enable discovery, engaging broad audiences across the world. There are many attributes that make citizen science an asset to the field of heliophysics, including agile collaboration. Agility is the effect to which a person, group of people, technology, or project can work efficiently, pivot, and adapt to adversity. Citizen scientists are agile—they are adaptable, efficient, and responsive. Citizen science projects and their underlying technology platforms are also agile in the software development sense—by utilizing beta testing and short timeframes to pivot in response to community needs. As they capture scientifically valuable data, citizen scientists can also bring expertise from other fields to scientific teams. The impact of citizen science projects and communities means citizen scientists are a bridge between scientists and the public, facilitating the exchange of information. These attributes of citizen scientists form the framework of agile collaboration. In this paper, we contextualize agile collaboration primarily for aurora chasers, a group of citizen scientists actively engaged in projects and independent data gathering. Nevertheless, these insights scale across other domains and projects. To advance the field of heliophysics over the next decade, we recommend the Committee take four actions: (1) Increase the prevalence of citizen science, (2) evolve policies and principles that consider citizen scientists as skilled transdisciplinary colleagues, (3) provide funding for relationship building and reciprocity efforts, and (4) leverage citizen science to facilitate collaborative efforts between related fields. Citizen science is an emerging yet proven way of enhancing the current research landscape. To tackle the next generation's biggest research problems, agile collaboration with citizen scientists will become necessary.

1 Introduction

Citizen science is a rapidly-growing and newly-formalized field that focuses on enabling the public to contribute to scientific discovery—small amounts of volunteered time by many people can contribute to a larger scientific goal (Shirky, 2010). A working definition of citizen science is "organized research in which members of the public engage in the processes of scientific investigations by asking questions, collecting data, and/or interpreting results" (Citizen Science Central). We note that the term "citizen science" is itself an unnecessary barrier to entry and is in the process of changing (Fuller, 2020). As consensus on a more appropriate term has not yet been reached (Cooper et al., 2021), we will use "citizen science" in this paper as a temporary measure. Citizen science encompasses multifaceted approaches, goals, and formats that span a broad spectrum of projects and are often defined by their characteristics. For a more in-depth characterization, we recommend reading the European Citizen Science Association's ten principles of citizen science. With such a breadth of attributes, as well as disparities in funding and support, the realization of citizen science ideals varies widely from project to project. Citizen scientist projects are well established and common in fields such as astronomy (e.g. Globe at Night; Garmany et al., 2008), and biology (Wiggins & Wilbanks, 2019), and the field of solar–terrestrial physics is finally seeing a growing number of projects (Knipp, 2015). Initiatives such as Aurorasaurus (MacDonald et al., 2015), HamSCI (Frissell et al., 2022, 2018), ScintPi (Rodrigues & Moraes, 2019), Solar Stormwatch (Barnard et al., 2014), and Solar Jet Hunter (Musset et al., 2021) have proven that citizen scientists can enable new scientific discoveries in aurora physics, ionospheric science, and heliophysics.

While the focus of citizen science is usually on the projects and their outcomes, the citizen scientists themselves ultimately drive discovery. The value these individuals and groups can bring to science is often realized but not formalized. As heliophysics explores new ways to use technology, collaborative teams, and innovative research methods to solve the field's biggest questions, citizen science emerges as a versatile way to leverage and connect with the public to drive the field forward.

In this white paper, we show how citizen scientists demonstrate qualities that make them a valuable asset to modern heliophysics. In Section 2, we explain how citizen scientists are highly agile. In Section 3, we show that citizen scientists know how to produce scientifically valuable data. In Section 4, we explain how the citizen scientists are "contributory experts" and "experiential experts" with transdisciplinary capabilities. In Section 5, we present ways citizen scientists can act as science "translators" to engage the broader public. In Section 6, we formulate recommendations based on our arguments, which outline the next 10 years of heliophysics incorporating citizen science. Finally, in Section 7, we offer concluding remarks.

2 Citizen scientists are highly agile

Citizen scientists maximize success and minimize time, leading to natural agility and efficiency in creating science results.

Agility is an important aspect of a person's scientific capability: the ability to think and understand quickly. In science, results-oriented outcomes can have many metrics, such as the frequency of publishing refereed journal articles. However, while they can be produced collaboratively, direct outcomes are not the only contributors to agility.

The human brain has a remarkable ability to spot differences in a continuum (Eysenck & Keane, 2015). In citizen science, this talent can be used in data-generating identification projects such as Aurora Zoo (Whiter et al., 2021) on the Zooniverse platform (Simpson et al., 2014), where citizen scientists categorize small-scale aurora features. In instances where data are being generated by the citizen scientists, this quality is even more important. Aurora chasers are a diverse group of photographers, amateur astronomers, and enthusiasts bound by a passion to witness and capture views of the aurora and auroral phenomena. In the field, aurora chasers are highly sensitive to the aurora and its appearance, recognizing when a deviation from natural patterns emerges. An example of this in effect was the citizen scientist identification of STEVE (Strong Thermal Emission Velocity Enhancement). Aurora chasers, mainly in the Alberta Aurora Chasers Facebook group, noticed an unusual aurora-type feature appearing equatorward of the main auroral oval during geomagnetic storms. This revelation is described in MacDonald et al. (2018). The identification of STEVE led to increased scientific interest, and in particular, the involvement of aurora chasers in formal research projects. One of the simplest ways aurora chasers can directly contribute to discovery is through the submission of their photos, which can then be analyzed by scientists (e.g. Hunnekuhl et al., 2021). These citizen scientists are highly experienced at recognizing abnormal conditions, and thus are frequently documenting previously unknown or understudied auroral phenomena (e.g. Dunes Aurora; Palmroth et al., 2019). Aurora chasers are also not pre-tuned to scientific assumptions about importance, meaning that as they pursue their own goals and motivations as skilled photographers, they capture unforeseen data. Aurora chasers have developed personalized workflows to gather their data, responding to changing conditions with sets of steps and decisions to track aurora and adjust camera settings. Their adaptability maximizes their capability to pivot rapidly and capture various atmospheric phenomena, tangential to the aurora itself (e.g. noctilucent clouds, meteors, satellites, subauroral phenomena, etc). This leads to discovery, particularly at disciplinary boundaries, like with STEVE at the subauroral boundary between high and middle latitudes.

The concept of agility also applies to software development and the processes of building citizen science projects. In software development, agile practices require discovery and solutions improvement through the collaborative effort of cross-functional teams with their end user(s), adaptive planning, continual improvement, and flexible responses to changes in requirements, capacity, and understanding of the problems to be solved (Beck et al., 2001). This adaptation of agility references projects using the latest technology, a short timeframe to pivot, and a lean production team that are agile themselves. An example of an agile citizen science project is the North Dakota Dual Aurora Cameras (NoDDAC; Ledvina et al., 2021), which provides live views of the aurora for the public, including aurora chasers. The aurora data are also archived and made open source, abiding by FAIR data use principles (Wilkinson et al., 2016). NoDDAC is a responsive, community resource that can be adapted quickly to integrate with other citizen science projects or scientific efforts—the project is agile. The agility of citizen scientists and citizen science projects allow for scientific discovery that can keep pace with an advancing research landscape.

3 Citizen scientists produce scientifically valuable data

Citizen scientists are extremely capable in terms of identifying scientifically valuable data.

One limitation often brought up by skeptics and critics of citizen science is the quality of data generated by citizen scientists. Numerous articles and studies have been published addressing these arguments (e.g. Specht & Lewandowski, 2018; Kosmala et al., 2016). It has been repeatedly demonstrated that the quality of citizen science data is correlated with the quality of its parent project's design to ask and answer appropriate scientific questions. Projects often train participants and include rigorous data cleaning practices. For example, the Aurorasaurus project crowd sources aurora sightings from Twitter using specific keywords and metadata, and the Twitter data are cleaned by project volunteers to create more robust datasets (Case et al., 2016). However, in instances where the data come directly from citizen scientists, as in the case of aurora chasers' photographs (see e.g. Figure 1), conscious decisions by the citizen scientists must be made to make the data scientifically useful. For research using citizen scientist images, metadata like exact camera location, time of capture, aperture, shutter speed, ISO, and white balance are critical information for scientists. Many studies involving citizen scientist contributions rely on triangulation methods that utilize multiple cameras and RAW photo manipulation to extract qualities of auroral features, such as true color, brightness, and spatial extent (e.g. Chu et al., 2020; Semeter et al., 2020). Other data quality controls are built into the data collection platforms (MacDonald et al., 2015). Online social media groups become nexuses for aurora chasers during geomagnetic storms, when photographers report conditions in real time. Standard practice in these communities is to include the location, time, and a general description of the activity (e.g. "naked-eye visible"). These metadata become valuable when submitting to validated platforms (e.g. Aurorasaurus) where data can be archived and made interoperable for research (see Figure 2). Furthermore, in the photographic community, it is standard practice to shoot in RAW picture mode. In this format, important camera settings are recorded in the image file. Color, brightness, and tonal data can not only be manipulated by the photographer to create a more pleasing aesthetic, but can also be analyzed by scientists. Aurora photographers in the field, then, are already capturing data that are scientifically useful. As the gap between consumer and scientific-grade cameras narrows, the role of the citizen scientist in photographic analysis of aurora and night-sky phenomena increases. Communities of aurora chasers are ready to step up to the plate and often utilize the latest commercial-off-the-shelf technologies they can access.

Figure 1: STEVE photographed by aurora chaser and Aurorasaurus citizen scientist Justin Anderson on March 13, 2021 in southern Manitoba.

4 Citizen scientists have both contributory and experiential expertise

Citizen scientists provide areas of expertise and perspectives that complement subject matter expert (SME) specialization.

Science as a field is trending toward large collaborative teams (Cheruvelil et al., 2014; Wang & Hicks, 2015; National Research Council, 2015) to accomplish research goals. The American Psychological Association notes: "Collaborative groups conducting team science research

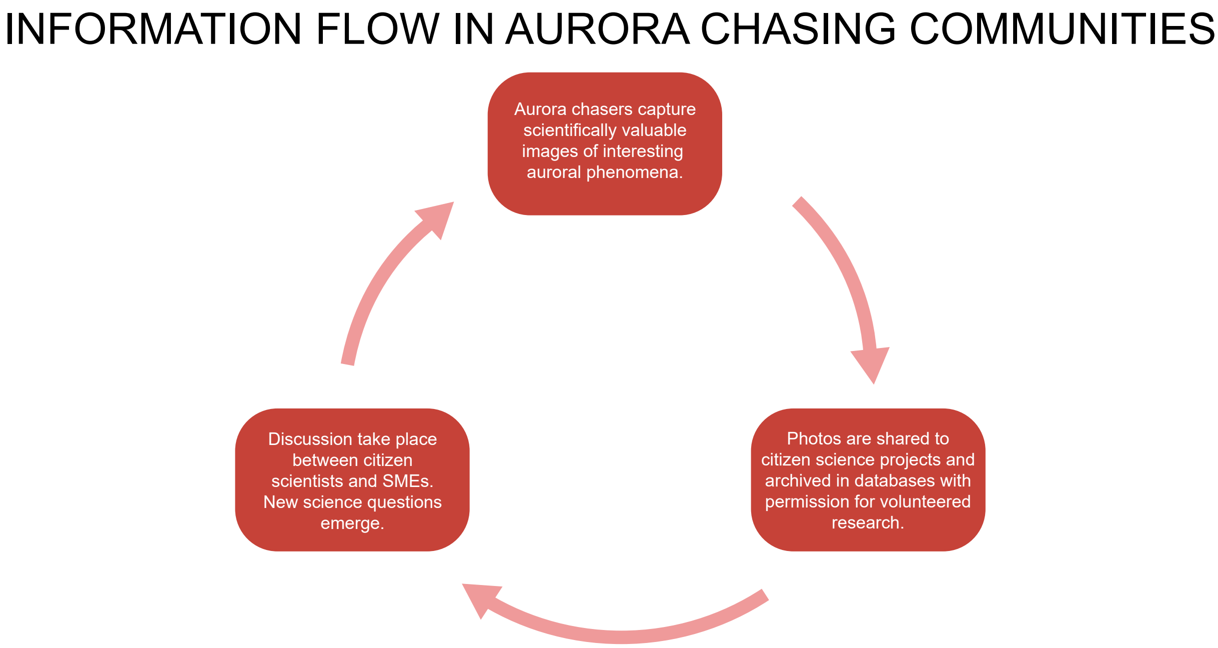

Figure 2: An example of how information flows through aurora chasing communities. SMEs and citizen scientists collaborate to identify scientific interests which can benefit from aurora chasers' observations.

may include [...] not only researchers, but also community members and policy makers (Calhoun, 2013). Through the process of sharing and expanding domains of expertise, research endeavors are informed by qualitatively rich discussions and possess greater potential for advancing science towards achieving desired outcomes." Perrault (2013) defines four kinds of expertise, two of which are especially relevant to citizen science. Contributory expertise is the capability of contributing to what is known about a topic, either in theory or practice. Experiential expertise is gained directly through personal experience.

Citizen scientists display varying types and degrees of these forms of expertise as they leverage preexisting skill sets for a project. Some projects, like the Ham Radio Science Citizen Investigation (HamSCI; Frissell et al., 2016) deliberately engage advanced-level, licensed amateur radio operators for their studies, who even have their own technical journals and conferences (see The National Association for Amateur Radio, Serra 2022, and white paper by Nathaniel Frissell: "Amateur Radio: An Integral Tool for Atmospheric, Ionospheric, and Space Physics Research and Operation"). Others seek more generalized skills such as pattern recognition. In aurora citizen science, advances in the study of the subauroral phenomenon STEVE (MacDonald et al., 2018; Semeter et al., 2020) could not have occurred without citizen scientists' contributory and experiential expertise in astrophotography. We note that at Aurorasaurus Ambassador meetings, aurora chasers draw on experiential, groundtruth knowledge derived from many nights of observation. The patterns they notice in STEVE events are consistent with scientific studies (Gallardo-Lacourt et al., 2018). Participants with skills in other fields can bring highly-applicable knowledge. Those with contributory expertise in history draw attention to rich archival resources (Hunnekuhl & MacDonald, 2020). Educators skilled in translating scientific concepts for public audiences help broaden participation. Data visualization professionals and engineers create tools to enhance data gathering (Kuzub, 2021). In addition, Traditional Knowledges (TKs) can engage with citizen science with the consent and agency of knowledge holders. For example, participants from Indigenous communities may choose to share cultural and spiritual knowledge about auroras, passed down over generations (Alaska Geophysical Institute). When shared voluntarily and within appropriate reciprocal, mutually beneficial relationships, TKs provide important insights (Carr & Ranco, 2017). When citizen scientists with knowledge in other fields engage with SMEs on projects, the citizen scientists develop additional skill sets, enhancing their experience. Spasiano et al. (2021) describe transdisciplinary citizen science as integrating a variety of scientific backgrounds and stakeholder perspectives to solve scientific problems. At its best, citizen science affirms generalists and knowledge holders with co-creative, transdisciplinary frameworks that equitably share power between experiential, cultural/spiritual, and academic types of knowledge (Bonney et al., 2009; Wilder Foundation, 2018). This necessitates actively engaging the goals and motivations that citizen scientists themselves bring to a project. It also requires recognizing and working to dismantle harmful power structures, as well as respecting and affirming data sovereignty, ownership of traditional knowledges, and knowledge holders' agency. Broadening participation means recognizing and affirming that there is an important place in scientific research for people who do not fit the "traditional" scientific roadmap. Far from "unskilled labor" (Blair et al., 2021), even while performing ostensibly simple tasks citizen scientists bring to a project a wealth of advanced knowledge spanning not only multiple academic fields, but also multiple types of knowledge.

As collaborators across disciplines, citizen scientists deserve reciprocity for all that they invest in a project. As with other forms of volunteerism, citizen science inherently functions as a social and psychological contract that exchanges social capital for labor and knowledge (Jones et al., 2006; Vantilborgh et al., 2012). Such reciprocity facilitates lasting participation (Hetland, 2020), but what this capital entails may vary and in many cases is best defined by the citizen scientists and communities themselves through relationship-building (Chitnis, 2018; Erickson, 2021; Yua et al., 2022). Many forms require funding, either directly (as in community compensation or individual honoraria) or indirectly (for example funding relationship-building, community expert liaisons, in-kind gifts, programmers to create rewarding user interfaces, or project managers to support participants). Funding for relationship-building and reciprocity is critical to the future success of scientific collaboration, including citizen science (Tachera, 2021).

5 Citizen scientists bridge scientists and the public

Citizen Scientists connect highly-specialized subject matter experts with the general public.

Cultivating relationships between scientists and science organizations is a key step in bringing awareness to science–society issues and helps inspire the public to be interested in science, technology, engineering, and mathematics (STEM) subjects. While many efforts in science aim to engage the public, citizen science projects need to be recognized and formalized, as they enable a high level of participation from citizen scientists who are connected to both SMEs and the general public. The goals of citizen science projects are not only to use the power of big data to drive science but to provide an educational experience for their users. Citizen scientists who are part of online communities can then share their knowledge with a passionate and receptive group. In online aurora chasing communities, citizen scientists can dialogue directly with SMEs and discuss findings in their data. This discussion helps inspire new science questions and more targeted observations, creating a positive feedback loop that sees citizen scientists as stakeholders and active participants in the research process. One analogy represents citizen science as a three-legged stool: The public, SMEs, and project infrastructure act as the legs supporting the mission of advancing science through discovery and education.

6 Recommendations

- **Increase the presence of citizen science in NASA science.**
  Over the next decade, citizen science will become integral to solving big-data problems, engaging the public with NASA efforts, and cultivating science that bridges disciplines. We recommend the Committee increase the funding for citizen science projects following the priorities laid out by the Heliophysics Strategic Working Group. We also recommend the Committee increase funding for individual science projects that incorporate citizen science data and focus on collaboration with the public.
- **Evolve policies and principles toward considering citizen scientists to be skilled transdisciplinary colleagues contributing volunteer time to projects.**
  Citizen scientists are often discussed on a population level, and as unskilled workers performing simple, repetitive tasks. However, this is not representative of citizen science communities in practice. Underestimating the transdisciplinary expertise citizen scientists bring to projects artificially devalues cultural and experiential knowledges. In addition, it slows collaboration efforts, hindering scientific discovery. We recommend that Diversity, Equity, Inclusion, and Accessibility (DEIA) principles be affirmed and put into practice, and co-creative structures be rewarded (Chaudhary & Berhe, 2020). In addition, pathways should be expanded by which citizen scientists can network with SMEs to pursue their science questions, and coauthorship by citizen scientists on publications and presentations should be encouraged. Plain language skills should be part of standard SME professional development in order to facilitate transdisciplinary collaboration goals. Finally, volunteer management principles related to labor ethics should be applied to citizen science research projects.
- **Provide funding specifically for relationship-building and reciprocity efforts.**
  Relationship-building is critical for the future of scientific collaboration and the future of citizen science. Gardner-Vandy et al. (2021) provide recommendations for every stage of relationship-building with a focus on Indigenous communities. Among other things, they emphasize the importance of long-term commitment, co-creating a shared vision, prioritizing the community as a source of credible information, and putting in the time and effort to build lasting, genuine relationships. These recommendations are essential to healthy collaborations with Indigenous groups, and many points apply more broadly across knowledge-sharing communities. We recommend the committee specify funding or increase current funding amounts for relationship-building and reciprocity efforts aimed at citizen scientist collaborations and projects. Reciprocity for collaborators or participants takes many forms, so we advise that the committee set aside money for direct compensation as well as indirect funding through relationship-building programs. Community relationships are long-term commitments, and this must be reflected in the funding structure.
- **Leverage citizen science projects to facilitate multidisciplinary efforts between related fields (e.g. magnetospheric and ionospheric physics communities).**
  Multidisciplinary efforts in heliophysics are important for identifying the risk and improving the resiliency of specific industries to space weather. Furthermore, current disciplinary silos

make answering systems-science questions more difficult and less streamlined. Citizen scientists can gather science data needed in interdisciplinary collaboration and act as a bridge between SMEs. We recommend that the committee amplify existing citizen science projects that are working towards these efforts as well as provide tools and resources for citizen scientists to contribute their own data to active research. HamSCI, a group of amateur HAM radio operators, is a prime example of how citizen scientists are creating research tools and scientific hardware that bridge disciplines. The annual HamSCI workshop invites citizen scientists and SMEs to present research efforts and identify areas where citizen scientists can collaborate on science projects. Examples of these collaborations can be found in Kazdan et al. (2019), Frissell et al. (2020), and Sanchez et al. (2021). More funding is needed to support groups and citizen science projects that facilitate interdisciplinary studies. Also, incorporating citizen science project data into knowledge commons like CDAWeb could be a way to introduce SMEs to citizen scientist data.

7 Conclusion

Citizen scientists are agile, competent, and skilled in other fields, and the aurora chasing community exemplifies these points. Aurora chasers are agile, able to adapt to changing conditions on the fly and adjust their data gathering processes in response. Through the collective agility of citizen scientists, projects themselves are often easily able to pivot and evolve. Citizen scientists are also highly competent in data gathering and analysis, and capable of recognizing scientifically significant patterns, as well as deviations from patterns.

Because they are not pre-tuned to scientific assumptions about importance, aurora chasers can capture unforeseen data that can lead to surprising discoveries. A culture of respect for scientific metadata already exists in aurora chasing communities. As the gap between science and consumer-grade cameras become smaller, citizen science data will play an increasing role in photographic analysis of aurora.

In addition, citizen scientists serve their communities as science communicators and facilitate scientific experiences, introducing new audiences to heliophysics. Online aurora chasing communities offer hubs for citizen scientists and SMEs to interact and collaboratively discuss citizen science projects, photography, and unusual aurora sightings. These conversations are highly productive: for example, they contributed to a new interest in the phenomenon known as STEVE.

An increasingly technology-driven and collaborative research environment in heliophysics will require novel ways to approach problems. Citizen science and its myriad benefits can enhance research, increase scientific discovery, and build relationships between communities. As a relational form of high-yield, transdisciplinary collaboration, citizen science requires funded reciprocity. We recommend that NASA increase funding for citizen science programs and related efforts.

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