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Agile collaboration: Citizen science as a transdisciplinary approach to heliophysics

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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 extent 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 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 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. 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.

KEYWORDS

citizen science, crowdsourced science, aurora, space weather, heliophysics

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.

For example, the European Citizen Science Association (ECSA, 2015) defines ten principles of citizen science. With a broad range of attributes, as well as disparities in funding and support, the realization of citizen science ideals varies widely from project to project. In this paper, we define values for citizen science to consider in the future and use aurora chasers as a "case study" example. In many instances, funding must be allocated for projects to realize these ideas. Ideally, citizen science projects engage members of the public who may act as contributors, collaborators, or project leaders and have meaningful roles in the project (principle 1). These citizen scientists can participate in multiple stages of a research project (principle 4), and are properly acknowledged when results are shared and published (principle 8). Citizen science projects have genuine scientific outcomes. These outcomes may be answering a research question or informing conservation action, management decisions or environmental policy (principle 2). In citizen science projects, feedback and communication are provided to participants (e.g., how their data are being used and what the research, policy, or societal outcomes are; principle 5). The "democratization" of science (principle 6) is a key principle of these projects, and data and methods are made open source and available to the public barring any privacy concerns (principle 7). The leaders of citizen science projects take into consideration legal and ethical issues surrounding copyright, intellectual property, data sharing agreements, confidentiality, attribution, and the environmental impact of any activities (principle 10). Finally, citizen science projects are evaluated at many stages for their scientific output, data quality, participant experience, and wider societal or policy impact (principle 9; Brandt et al., 2022).

Citizen science projects are well established and common in fields such as astronomy (e.g., Globe at Night; Garmany et al., 2008), and biology (Wiggins and Wilbanks, 2019), and the field of solar–terrestrial physics is finally seeing a growing number (Knipp, 2015). Initiatives such as Aurorasaurus (MacDonald et al., 2015), the Ham Radio Citizen Science Investigation HamSCI (HamSCI; Frissell et al., 2022a; Frissell et al., 2022b; Frissell et al., 2018), ScintPi (Rodrigues and Moraes, 2019), Solar Stormwatch (Barnard et al., 2014), sonification techniques (e.g., Archer et al., 2022), Solar Jet Hunter (Musset et al., 2021) have proven that citizen scientists can contribute to new scientific discoveries in aurora physics, ionospheric science, and solar physics.

While the focus of science is usually on the projects and their outcomes, the citizen scientists themselves ultimately drive discovery. 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 paper, we show how citizen scientists demonstrate qualities that make them valuable assets to modern heliophysics. In **Section 2**, we explain how citizen scientists are highly agile. In **Section 3**, we show that citizen scientists can produce scientifically valuable data. In **Section 4**, we explain how 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. Finally, in **Section 6**, we offer concluding remarks.

2 Citizen scientists are highly agile

Citizen scientists maximize success and minimize expended time, leading naturally to 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 evidence of agility (our context of agility in science is adapted from Buffone, 2021).

The human brain has a remarkable ability to spot differences in a continuum (Eysenck and Keane, 2015). In citizen science, this talent can be applied to data-generating identification projects such as Aurora Zoo (Whiter et al., 2021) on the Zooniverse platform (Simpson et al., 2014), in which citizen scientists categorize small-scale aurora features. In instances where data are generated by the citizen scientists themselves, 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 capability was the citizen scientist identification of STEVE (Strong Thermal Emission Velocity Enhancement). Aurora chasers, particularly in the Alberta Aurora Chasers Facebook group, noticed an unusual aurora-type feature appearing equatorward of the main auroral oval. 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 (e.g., Archer et al., 2019; Martinis et al., 2022; Nishimura et al., 2022). 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 frequently document 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 discoveries, particularly at disciplinary boundaries, as with STEVE in the subauroral region 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 refinement, and flexible responses to changes in requirements, capacity, and understanding of the problems to be solved (Beck et al., 2001). This conceptualization of agility refers to 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 to 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; Halford et al., 2022). 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 the advancing research landscape.

3 Citizen scientists produce scientifically valuable data

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

Skeptics and critics of citizen science often mention concerns about the quality of data generated by citizen scientists. Numerous articles and studies have been published addressing these arguments (e.g., Specht and Lewandowski, 2018; Kosmala et al., 2016), repeatedly demonstrating 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 quality assurance and quality control practices for their data. For example, the Aurorasaurus project crowdsources aurora sightings from Twitter using specific keywords and metadata, sightings arevoted on in real-time for initial confirmation per training guidelines, and the Twitter data are then 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 documented to make the data scientifically useful. 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 curated for research (see **Figure 2**). Furthermore, in the photographic community, it is advised 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 technological 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.

In the broader Heliophysics community, low-cost science-grade instruments are becoming available to the public. For example, ScintPi (Rodrigues and Moraes, 2019) or magnetometers (Beggan and Marple, 2018). Even native sensors in smartphones can enable citizen science projects (e.g., Crowdmag; Nair et al., 2014).

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; National Research Council, 2015; Wang and Hicks, 2015) to accomplish research goals. The American Psychological Association notes: "Collaborative groups conducting

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

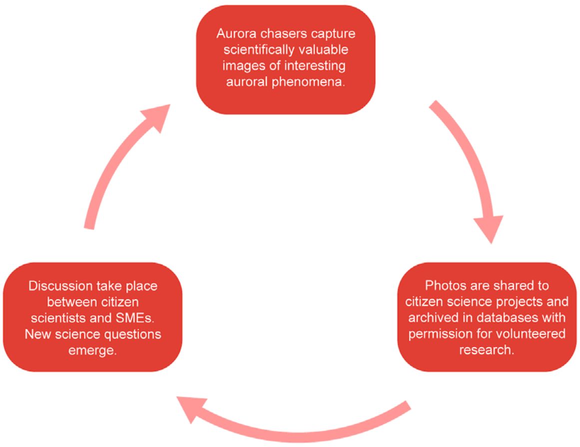

FIGURE 2
An example of how information flows through aurora chasing communities. Subject matter experts (SMEs) and citizen scientists collaborate to identify scientific interests which can benefit from aurora chasers' observations.

team science research may include […] not only researchers, but also community members and policymakers (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 developed 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 HamSCI deliberately engage advanced-level, licensed amateur radio operators for their studies, who have their own technical journals and conferences (see The National Association for Amateur Radio, Serra 2022,; Frissell et al. (2022a); Frissell et al. (2022b) 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 (e.g., 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 (e.g., Hunnekuhl and 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 (e.g., Kuzub, 2021). In addition, Traditional Knowledges (TKs) can engage with traditional, Western 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 (e.g., Alaska Geophysical Institute). When shared voluntarily and within appropriate reciprocal, mutually beneficial relationships, TKs provide important insights (Carr and Ranco, 2017; Tengö et al., 2021; Bhawra, 2022). When citizen scientists with knowledge in other fields engage with SMEs on projects, the citizen scientists develop additional skill sets, enhancing their experience. SMEs also report reciprocal, synergistic relationships.

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 various types of expertise (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 knowledge, 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 professional science 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 deserve special recognition 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.

Using Aurorasaurus as a prime example, on the project's website are tutorial articles explaining how to submit aurora reports along with targeted scientific information about the aurora and how it is formed. Those who are interested can further explore the science behind the aurora and the principles of citizen science through blog articles and other content. Founded and run by a space physicist SME (MacDonald et al., 2015), the project provides clear and concise scientific information to enhance the citizen science experience, equipping the volunteer with *accurate* knowledge that they can then use in their daily lives. This simple yet powerful interaction is happening in hundreds of citizen science projects across disciplines and in the field of heliophysics.

For example, HamSCI brings together professional scientists and amateur radio operators at the annual HamSCI workshop. These types of cross-disciplinary gatherings help forge stronger bonds between SMEs and the science-oriented public. Furthermore, HamSCI's personal space weather station is an effort led by a team of professional scientists but beta tested and validated with the help of volunteers from the amateur radio community (e.g., Hobart et al., 2021; Joshi et al., 2021; Kim et al., 2022).

Solar Jet Hunter, a solar physics citizen science project hosted on the Zooniverse platform, recruits volunteers to identify jets of plasma from extreme ultraviolet images of the Sun. Built into the project itself are educational tutorials explaining the datasets, the solar jet phenomena, and why they are important to scientists. An interactive forum allows participants to ask questions, discuss findings, report bugs and enhancements, and communicate directly with SMEs. Projects like Solar Jet Hunter engage are targeted at anyone with a scientific interest, not just those in the space science community. As mentioned in **Section 4**, engaging a diverse audience is important for leveraging multiple perspectives.

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 communicate 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 infrastructures act as the legs supporting the mission of advancing science through discovery and education.

6 Conclusion

Citizen scientists are agile, competent, and skilled. 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 more 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. As the gap between science and consumer-grade cameras becomes ever 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 for others, 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. Citizen scientists can gather science data needed in interdisciplinary collaboration and act as a bridge between SMEs. Multidisciplinary efforts in heliophysics are important for identifying the risk and improving the resiliency of specific industries to space weather (Ledvina et al., 2022a; Ledvina et al., 2022b). Over the next decade, citizen science will become integral to solving big data challenges, engaging the public with NASA efforts, and cultivating science that bridges disciplines. Over the next decade and beyond, the agility of citizen science will become an important tool in solving grand challenges in heliophysics. Agency-specific recommendations reflecting these sentiments can be found in the white paper of the same title submitted to the 2024-2033 Heliophysics Decadal Survey (Ledvina et al., 2022a; Ledvina et al., 2022b).

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

VL conceived the work, was responsible for the organization of this article, and contributed to all sections. LB and EM made substantial contributions to all sections of this article. JA provided a photograph of the STEVE phenomenon. All other authors listed helped analyze and contribute to the article before submission.

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Conflict of interest

JK was employed by Jufa Intermedia-Capture North.

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