



Citizen Science in Space and Atmospheric Sciences: Opportunities and Challenges

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Abstract

Citizen science (also referred to as participatory science or community science), in which members of the general public contribute to scientific research, is not a new concept, as early examples of such studies can be found a couple of centuries ago. With the advancement of technology in an increasingly connected world, it has never been easier to engage citizen scientists in research projects. In this paper, we review citizen science initiatives and projects in the fields of atmosphere and space physics, including both early observation campaigns prior to the twenty-first century and recent projects. Ongoing initiatives take a broad range of forms, from the collection of data by citizen scientists to their involvement in the data analysis process and to the hosting of instruments in non-scientific public structures. We also discuss some of the challenges specific to citizen science, such as training citizen scientists, maintaining their engagement, ensuring reciprocity, managing citizen science data, interfacing the academic and citizen scientist communities, and funding citizen science. To these challenges we suggest possible solutions, and we highlight the unique opportunities offered by recent software and hardware developments. These game-changing opportunities are foreshadowing the dawn of a new era for citizen science – and hence for science in general and atmosphere and space physics in particular.

Keywords Citizen science · Participatory science · Space physics · Atmospheric physics

Article Highlights

- Modern technology creates unprecedented opportunities to leverage citizen science in atmosphere and space physics
- Citizen science is not limited to data collection but can also take the form of fully collaborative approaches
- Challenges to overcome include citizen scientist engagement, data management, cross-community communication, and funding

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1 Introduction

The National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) both recognise the valuable role of citizen science, defining it in similar terms. NASA describes citizen science projects as those that “rely on volunteers” and are held to the same rigorous standards as any NASA science project. ESA, on the other hand, emphasises that our interconnected world offers a solution in the form of “citizen scientists” – volunteers who donate their time, expertise, or mobile phone power to advance scientific research.

In the recent years, the term “citizen science” has been debated, on the basis that the word “citizen” might not be the best choice for promoting the inclusion of participants from diverse backgrounds. Eitzel et al. (2017) explored the impact of terminology and highlighted the caveats associated with each choice of term for referring to the concept of citizen science as well as the participants (from the academic world and from the general public) in such projects. Alternative phrases have been proposed and adopted by some institutions and research fields, such as “community science”, “participatory science”, but a clear consensus at international level is still to be reached. It is unclear whether a change in terminology would be the best approach to improve diversity and inclusion (Cooper et al. 2021). In this paper, we will therefore use “citizen science”, “citizen scientists” and “academics/professional scientists”, keeping in mind the possible shortcomings of these choices of terms.

Regardless of the chosen terminology, a theoretical framework has been devised for citizen science over the past couple of decades, starting from data collection projects relying on the participation of citizen scientists and designed to also include outreach and educational benefits (Bonney et al. 2009b). This framework has been expanded to a model distinguishing five main typologies of citizen science (Bonney et al. 2009a; Shirk et al. 2012; Spasiano et al. 2021):

1. *Contributory*: citizen scientists are data providers, while the project design and data analysis are carried out by professional scientists;
2. *Collaborative*: professional scientists typically design the project, and citizen scientists are not only data providers but are also actively involved in the analysis and interpretation of the data and in the dissemination of the results;
3. *Co-created*: citizen scientists and academics are both involved in all the aspects of the project, from project design to data analysis and to the dissemination of findings;
4. *Contractual*: professional scientists are mandated by the members of the public to carry out a research project designed by the community;
5. *Collegial*: citizen scientists carry out a research project independently, with little to no input from professional scientists.

One of the earliest examples of citizen science in atmosphere and space sciences is the 1715 total solar eclipse observations by volunteers across central England (Halley 1715). Marshall et al. (2015) gave a review of citizen science in astronomy as it stood about a decade ago. They highlighted not only the diversity of ways for the public to participate in scientific research, but also the unique strengths of citizen science making it complementary with great observatories and machine learning methods. The recent review paper by Fortson (2021) echoes some of those points but for the field of

space science, and builds around examples illustrating concrete discoveries and ongoing efforts which will be addressed in our paper.

The advancement of technology in recent years has allowed the scientific community to develop and deploy a larger number of ground-based and space-borne instruments across various disciplines. However, observational gaps still exist, and citizen scientists' observations can help bridge these gaps, enhancing our understanding of the world we live in. Figure 1 shows the example of optical imaging instruments dedicated to studies of auroral and auroral-related phenomena in North America. The fields-of-view of the Time History of Events and Macroscale Interactions during Substorms (THEMIS) and Transition Region Explorer (TREx) all-sky imagers are indicated with red circles. During the extreme geomagnetic storm which started on 10 May 2024, hereinafter referred to as the Gannon/Mother's Day Storm, the auroral oval extended equatorward from the area covered by those optical instruments. The figure shows an image of the aurora taken by the Visible Infrared Imaging Radiometer Suite (VIIRS) Day Night Band (DNB) onboard the Suomi National Polar-orbiting Partnership (NPP) satellite taken at 08:13 UT on 11 May 2024, in which it is clear that THEMIS and TREx instruments largely missed the auroral activity at that time. In contrast, citizen scientist reports of auroral observations, collected via an online survey (Grandin et al. 2024) and indicated with green dots highlight the potential of leveraging images taken by citizen scientists during such extreme geomagnetic events.

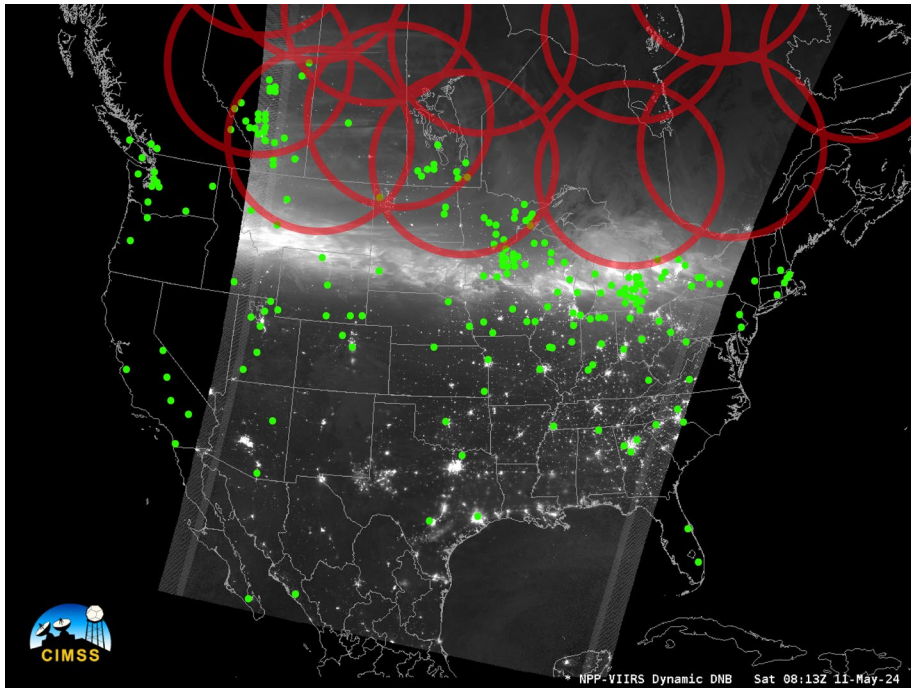


Fig. 1 Image from the VIIRS DNB instrument onboard the Suomi NPP satellite showing a portion of the auroral over the central USA. This image was captured during the Gannon/Mother's Day storm on 11 May 2024 at 08:13 UT. Citizen science reports of aurora obtained via an online survey (Grandin et al. 2024) are shown as green dots. The fields-of-view of THEMIS and TREx all-sky imagers are overplotted in red.

In addition to the recent example above, belonging to the contributory citizen science typology, initiatives such as the amateur radio hobby (ham) community (discussed in Sect. 2.2), Aurorasaurus (MacDonald et al. 2015, discussed in Sect. 2.4), and the “Auroral Research Coordination: Towards Internationalised Citizen Science” (ARCTICS) project supported by the International Space Science Institute (ISSI) in Bern, Switzerland (discussed in Sect. 3.1) show features from the collaborative and even co-created typologies.

The objective of this article is to provide an overview of citizen science endeavours in the fields of heliophysics (the study of solar–terrestrial interactions, covering solar, solar wind, magnetospheric, ionospheric, and upper-atmospheric physics) and atmospheric sciences (including meteorology, atmospheric chemistry, atmospheric dynamics). In Sect. 2, we review the existing literature resulting from citizen science contributions in atmosphere and space physics. Section 3 presents selected ongoing initiatives involving citizen scientists to further advance those fields. Various hurdles and challenges that currently hinder citizen science to fully flourish are discussed in Sect. 4. New opportunities that can open a new era in citizen science are highlighted in Sect. 5, and we conclude with closing words in Sect. 6.

2 Citizen science contributions to atmosphere and space physics

Citizen science has led to various types of contributions to atmosphere and space physics. In this section, we first briefly review early campaigns of auroral observations involving members of the general public during the nineteenth and twenty-first century. Then we turn on to discussing three main aspects in which citizen science has recently facilitated scientific advances in atmosphere and space physics: the establishment of well-organised communities such as that of the amateur astronomers and amateur radio hobby (ham), the organisation of coordinated observation campaigns for specific purposes, and the collection of citizen science data which have enabled serendipitous discoveries.

2.1 Early citizen science campaigns in atmosphere and space sciences

During 1846–1855, the Finnish Science Society and the Magnetic Observatory of the University of Helsinki (nowadays Finnish Meteorological Institute, FMI) organised a large observation programme. It did not only include meteorological observations but also a broad range of other natural phenomena such as the departure times of ice in water bodies and departures and arrivals of migratory birds. Within the framework of the programme, about 3000 observations of the aurora were also gathered throughout the duration of the programme (1846–1855). The observers were mainly local members of the general public or priests. A summary of observations was published in 1860 by Adolf Moberg; the yearly number of nights during which the aurora was observed showed good correspondence with the local magnetic activity as measured with the average A_k index from the Helsinki Observatory magnetometer (Nevanlinna 2009).

Another successful citizen science observation campaign targeting the aurora was planned and executed during 1878–1879 by Sophus Tromholt of the Danish Meteorological Institute. Tromholt sent 600 letters to vicarages and sea captains encouraging the receivers to make auroral observations. With his expanded observation network, he collected 839 observations from 132 stations in Denmark, Sweden and Norway over 154 nights (Stauning 2011). While Tromholt’s interpretation of the collected data were not always

correct, he did reach an important conclusion: he noted that almost every night there was a place within the Nordic countries where the aurora was visible, despite the campaign being held during solar minimum.

In the early years of atmospheric sciences, theme years like the International Polar Year (IPY) and the International Geophysical Year (IGY) played an important role in launching observation campaigns towards the general public and initiating collaboration. During the second IPY in 1932–1933, the FMI and Sodankylä Geophysical Observatory (SGO) started observation campaigns involving the general public. In Denmark, much effort was put into creating northern light observation manuals, instructions, and making them generally available (Stauning 2011). In the following years, similar campaigns by independent groups were carried out in New Zealand, the USA and Canada (1953 by Cornell University/National Geophysical Society), and the UK (1940 by the British Astronomical Association). In many cases the co-operation combined scientific associations and research organisations (Schröder 2007). In Sweden, the Uppsala Ionospheric Observatory started a public observation gathering campaign in 1953 relying on prepaid postcards, which involved about 20 participants in the north and central parts of the country. The conclusion of this campaign was that “this method had some value for a coarse survey of the auroral activity”, and that “experience was also gained of the difficulties of this method” (Stoffregen 1955).

Many observing communities were already active when the IGY started in 1957. The IGY organising committee provided observation instructions and manuals to support the communities participating in observation gathering. Many of these campaigns targeted amateur and professional astronomers, who had prior experience in observing the night sky (Schröder 2007). Other participating professionals included plane pilots and sailors (Schröder 2007; Nevanlinna 2009). During the IGY (1957–1958), observations were collected from the Soviet Union, Germany, France, the UK, the USA, and Canada. The US National Committee of the IGY reported receiving 16,000 auroral observations from 424 individual observers during the first 11 months of operation (Schröder 2007). In Northern Europe, new IGY observation gathering campaigns were launched by both the Uppsala Ionospheric Observatory in Sweden and the FMI. During these years, observers participated in the campaign by sending in letters and observation cards of the aurora events (Nevanlinna et al. 2024). Among the results of this worldwide effort, valuable observations of the aurora at middle and low latitudes were made, enabling a better characterisation of its distribution during exceptionally active geomagnetic conditions (Schröder 2007).

After the IGY period, the interest towards gathering additional information from the general public remained. In 1976, a special northern lights section was established in the Ursa Astronomical Association in Finland. The section continued to receive observations over mail and publish summaries of them in a periodical titled *Ursa Minor* (Karttunen 2021). The section moved to digital observation gathering in the beginning of the 2000s. The observation campaign still continues today in the Taivaanvahti/Skywarden observation system (see Sect. 2.4).

2.2 A well-established community: amateur radio hobby (ham)

Since its establishment in the early 20th century, members of the amateur (ham) radio hobby have significantly contributed to both atmospheric and space physics (Yeang 2013; Frissell et al. 2023), as well as the growth of the wireless communications industry (Rapaport 2022, 2023). Amateur radio is a radio service with global participation that requires

its licensees to (a) demonstrate a basic knowledge of radio engineering and science, and (b) not have a pecuniary interest in the transmissions they make. Amateur radio bands are spread throughout the radio spectrum, many of which allow for long-distance communications due to ionospheric refraction and other atmospheric effects. As such, amateur radio communications are highly susceptible to both space and atmospheric weather. This unique combination of required technical knowledge, volunteerism, and susceptibility to space and atmospheric weather makes the amateur radio operators an ideal group for producing citizen scientists. The trans-Atlantic tests were amateur radio experiments in the early 1920 s coordinated by the American Radio Relay League (ARRL) and Radio Society of Great Britain (RSGB) that were critical to early understanding of the ionosphere and the development of the field of atmospheric science (Yeang 2013). Amateur radio operators were later involved in the 1957–1958 IGY ionospheric experiments (Duquet 1959; Southworth 1959, 1960; Dora 2023).

Today, advances in signal processing, computers, and internet connectivity have enabled amateurs to build global-scale networks of automated receivers that have now generated over a solar cycle of ionospheric observations. These networks include the Weak Signal Propagation Reporter Network (WSPRNet, <https://www.wsprnet.org/>, <http://wsprdaemon.org/>; Taylor and Walker 2010), PSKReporter (<https://pskreporter.info/>), and the Reverse Beacon Network (RBN, <https://reversebeacon.net/>). Data from these networks have already been used to study ionospheric effects of solar flares and geomagnetic storms (Frissell et al. 2014, 2019), ionospheric effects of solar eclipses (Frissell et al. 2018), plasma cutoff and single-mode fading (Perry et al. 2018), Sporadic E (Deacon et al. 2021, 2022), near-vertical incidence skywave propagation (Walden 2012, 2016; Witvliet et al. 2015, 2016; Witvliet and Alsina-Pagès 2017), grey-line propagation (Lo et al. 2022), and validation of ionospheric models (Chartier et al. 2023; Frissell et al. 2018). Figure 2, originally from Frissell et al. (2019), illustrates the use of amateur radio networks for sensing the ionospheric impacts of solar flares. Here, two X-class flares are observed on 6 September 2017 by the United States National Oceanographic and Atmospheric Administration Geostationary Operational Environmental Satellite X-Ray Sensor (NOAA GOES XRS) when Europe was in daylight. Both flares caused a dramatic radio blackout on the 7, 14, 21, and 28 MHz amateur radio bands. Such observations are useful for studying the spatial and temporal evolution of the ionospheric response to solar flares, as well as directly observing how flares impact certain types of terrestrial communications systems.

In addition to using data from purely amateur-deployed networks, formal collaborations between academics and the amateur radio community are now under way to establish a distributed array of Personal Space Weather Stations (PSWS) to address the unique needs of scientific investigation (Collins et al. 2021, 2023; Gibbons et al. 2022). The PSWS network, as well as many of the amateur radio studies cited here, are led by the Ham Radio Science Citizen Investigation (HamSCI) project, which is discussed below. Frissell et al. (2023) provides a more comprehensive review of amateur radio citizen science contributions, including a table of studies using amateur radio data and techniques published in both the professional and amateur literature.

Building upon the long tradition of citizen science and engineering of the amateur radio community, HamSCI (<https://hamsci.org>) was established in 2015 (Frissell et al. 2015, 2023) following the publication of Frissell et al. (2014) in preparation of the 2017 Great American Eclipse (Frissell et al. 2018). HamSCI is now an international collaboration that seeks to bring together amateur radio and professional research communities for mutual benefit. With over 3 million licenced operators worldwide from diverse backgrounds united by a common interest in the advancement of wireless communications and science, the

06 Sep 2017
Ham Radio Networks
N Spots = 185579
RBN: 14%
WSPRNet: 86%

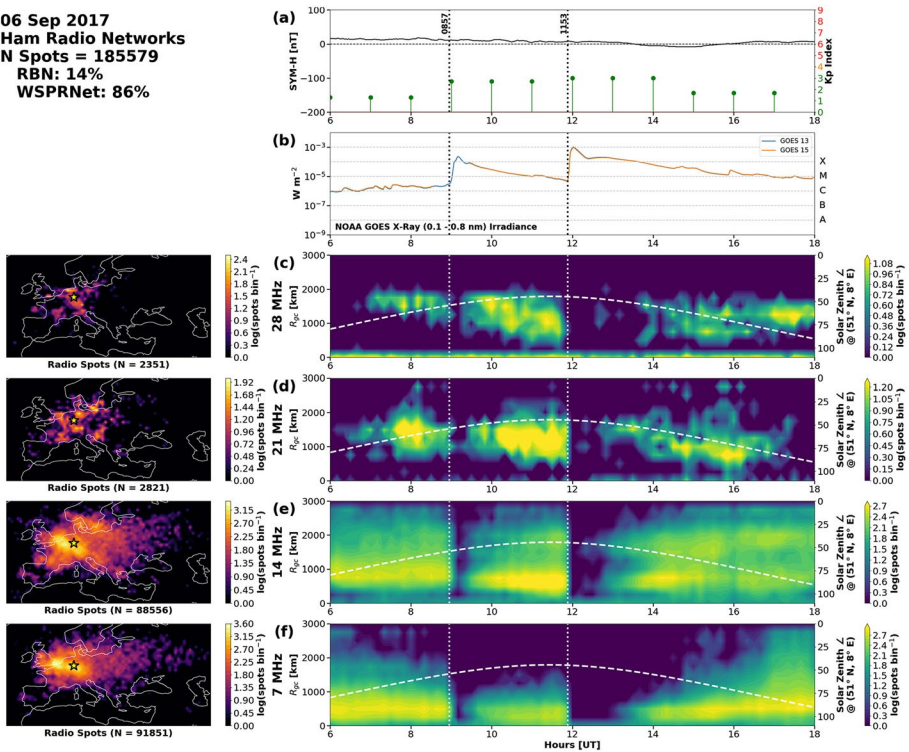


Fig. 2 Example of solar flare ionospheric impacts observed by amateur radio observing networks over Europe on 6 September 2017. (a) SYM-H (black line) and Kp (coloured stems). (b) GOES-13 (blue) and GOES-15 (orange) XRS 0.1–0.8 nm X-ray measurements. Flares are observed at 08:57 UTC (X2.2) and 11:53 UTC (X9.3) and indicated with dotted vertical lines. (c–f) Two-dimensional contour histograms of RBN and WSPRNet spot data for the 28-, 21-, 14-, and 7-MHz amateur radio bands, respectively. Bin size is 250 km $\times$ 10 min. To the left of each histogram is a map showing the log density of TX-RX midpoints of all spots used in the histogram. The white dashed lines on the histograms show the solar zenith angle computed for (51°N, 8°E), the point indicated by the yellow star on each map. Radio blackouts across the HF bands can be seen in response to the solar flares in the GOES data. From Frissell et al. (2019), reproduced with permission.

amateur radio community is ideal for citizen science collaborations. HamSCI engages amateurs and professionals alike through online email forums, weekly telecons, its website, annual in-person workshops, collaborations with amateur radio national organisations and media, and participation in professional and amateur conferences alike. HamSCI actively works to encourage its members to participate in all stages of the scientific process, including experiment design, instrument engineering, data collection, data analysis, and publication, while also providing education, outreach, enrichment, and networking opportunities for its participants.

2.3 Citizen science campaigns to characterise other atmospheric processes

From the beginning of the space age, initiated by the IGY activities, citizen scientists contributed to the very first scientific results, by measuring and reporting the time of overflight

of Sputnik and other early artificial satellites. These observations were collected at least in the Royal Aircraft Establishment (RAE) in the UK and in the Smithsonian Astrophysical Observatory in the USA (McCray 2006). Together with dedicated optical and radio-tracking observations, the reports were analysed in terms of changes in orbital period. This reflected the changing density of the neutral upper atmosphere through which the satellites were moving, and the strong effects of solar illumination and solar activity on those variations (King-Hele 2005). Observed changes in the orientation of the orbit could also be related to the gravitational effects of Earth's flattening.

Prior to the internet-age, collaboration with amateur observers has provided valuable data into analysis of noctilucent clouds. Long-lasting observation gathering from several countries provided input of occurrences statistics of the phenomenon (Gadsden 1998).

Citizen science studies of the atmosphere include observation campaigns which have led to the discoveries of new halo phenomena. The Finnish Halo Observing Network (Pekkola 1991), active during the 1980s and 1990s, consisted of a few tens of volunteer observers who photographed and documented atmospheric halos. Their work, under the Ursa Astronomical Association, has led to several publications on various types of halos (Riikonen and Ruuskanen 1994; Sillanpää et al. 1999), including a proposed halo formation mechanism involving pollen (Parviainen et al. 1994). The Finnish Halo Network's tradition continues in Ursa's atmospheric section and focus has since then moved into analysing observations in Taivaanvahti/Skywarden (see Sect. 2.4). This has led to the discovery of several new halos by the Finnish and Swedish amateur observer communities (Moilanen and Gritsevich 2022).

Citizen science has also been utilised to aid the investigation of atmospheric phenomena during solar eclipses (Können and Hinz 2008) and solar eclipse effects on meteorology. This can be done by providing spatially dense networks of regular meteorological observations, e.g. as in the NEWEx project to study the partial solar eclipse over the UK in March 2015 (Barnard et al. 2016). This campaign collected over 15,000 meteorological observations from 309 locations across the UK, allowing eclipse-driven temperature and wind changes to be studied in great detail. The design and evaluation of the success of NEWEx as a citizen science project is discussed in Portas et al. (2016), where it was reported that 2600–3500 of the project's participants were school children, demonstrating the importance of citizen science projects in inspiring the younger generation to take part in science, technology, engineering, and mathematics activities.

One of the most successful citizen science programmes led by NASA to date is the Global Learning and Observations to Benefit the Environment (GLOBE) project, in which over 55,000 observations of clouds from 99 countries were made by citizen scientists during a one-month worldwide campaign (Colón Robles et al. 2020). While the majority of the observations, in absolute numbers, came from Europe and North America, a non-negligible fraction of the reports originated from the other continents, in particular regions identified as “Near East & North Africa”, “Latin America & Caribbean”, and “Asia & Pacific”, thanks to sustained advertisement of the ongoing initiative in the news media in multiple languages.

2.4 Serendipitous discoveries and collaborative databases

Enthusiastic citizen scientists have become instrumental in new discoveries. Notable recent examples from space physics highlight this trend. The earliest example is that of a phenomenon dubbed STEVE (Strong Thermal Emission Velocity Enhancement;

MacDonald et al. 2018). STEVE was brought to scientists' attention by talented and engaged auroral photographers. The combination of citizen scientists' images and scientific instrumentation has been fuelling numerous studies of this unique phenomenon among the scientific community. Citizen scientist data continue to play a crucial role in identifying physical characteristics such as the emission's altitude, the relationship between stable auroral red (SAR) arcs and STEVE (e.g. Martinis et al. 2022), and the details of the picket fence structure associated with STEVE (Semeter et al. 2020). A very recent study by Nanjo et al. (2024) revealed the existence of a dawnside counterpart of STEVE, occurring polewards from the auroral oval; this phenomenon was also brought to the attention of academics by a citizen scientist who was following the stream of real-time classification of auroral images known as Tromsø-AI (<https://tromsoe-ai.cei.uec.ac.jp/>, Nanjo et al. 2022). Another auroral phenomenon, known as dunes, was discovered and studied thanks to collaborations between academics and citizen scientists. The photographs of the wave-like structuring in the diffuse aurora, taken by citizen scientists, have enabled the estimation of the altitude of the dunes via triangulation (Palmroth et al. 2020). They have also enabled the determination of the dunes' spatial characteristics (wavelength, extent) and drift speed with respect to the ground, thus providing valuable elements to identify their formation mechanism (Grandin et al. 2021).

Citizen scientists have also played a key role in the investigations of fragmented auroral emissions (FAEs). Appearing as small splinters of green emission, either alone or in chains, these features had not been discussed in the scientific literature until 2021 (Dreyer et al. 2021). FAEs are small-scale and usually last under a minute, so resolution limitations likely prevented research until recent years. The Auroral Structure and Kinetics (ASK, Dahlgren et al. 2016) instrument located on Svalbard, Norway, captures high-resolution images of a small region of sky (10 km × 10 km at E-region altitudes) around the magnetic zenith in three different wavelengths (673.0 nm from molecular nitrogen, 777.4 nm from atomic oxygen, and 732.0 nm from oxygen ion). As the instrument captures a high volume of images, the Aurora Zoo project (www.aurorazoo.org) was developed for citizen scientists to view and classify what types of auroral forms appear in each image. Through this system, one event with FAEs was classified by a group of citizen scientist and then further studied by Whiter et al. (2021). After the event was identified, it was possible to study the motion and emission wavelengths of the features and discuss possible generation mechanisms.

The above examples illustrate how such serendipitous discoveries are facilitated by having citizen scientists report observations that they deem unusual. Collaborative databases are efficient platforms to enable not only the collection of observations made by citizen scientists, but also their archival and metadata management. Three prime examples of such collaborative databases can be mentioned in auroral and atmospheric sciences: European Severe Weather Database, Skywarden, and Aurorasaurus.

The European Severe Weather Database (ESWD; www.eswd.eu) was established in 2006 for gathering extreme-weather-related observations from all over Europe. Operated by European Severe Storms Laboratory, the database collects observations of extreme winds, heavy rains, hail and different types of funnel clouds. ESWD currently receives between 20,000 and 30,000 reports per year. The database's long history of open, content-verified data has been used in various publications including forecasting, hazard estimation and evaluating weather trends (Dotzek et al. 2009).

In Australia, the Fireballs in the Sky project (Day et al. 2019) enables citizen scientists to report fireball observations via a mobile application. These observations have led

to the successful recovery of meteorites and to the reconstruction of their trajectories, which contributes to refining our understanding of the formation of the Solar System.

Created in 2011, Skywarden (whose original name in Finnish is Taivaanvahti; <https://www.taivaanvahti.fi/>) is a catalogue of astronomical and atmospheric observations maintained by the Ursa Astronomical Association (Finland). In Skywarden, citizen scientists can report observations of a wide range of phenomena occurring in the sky, from comets and fireballs to rare cloud formations and halos, including auroral and subauroral emissions. To date, it contains over 122,000 observations, among which about 70,000 are of atmospheric phenomena (rare cloud formations, airglow, atmospheric halos, thunderstorms, and transient luminous events) and about 15,000 are currently of auroral and subauroral emissions (aurora, STEVE, SAR arcs...). The observation programme for the Sun also covers details like sunspots and flares, which many amateurs follow by using narrow-band filters or radio telescopes.

Aurorasaurus.org is an award-winning citizen science project that maps the aurora in real time with reports from citizen scientists (MacDonald et al. 2015). An example of map generated from Aurorasaurus reports is shown in Fig. 3. Scientific goals include improving the real-time specification of aurora knowledge and models, as well as engaging volunteer observations to increase the study and understanding of auroral phenomena (Case et al. 2015, 2016b; Kosar et al. 2018). The project also involves the citizen scientists in the research process, encouraging them to lead themselves the results, observations, and analysis (Hunnekuhl and MacDonald 2020; Semeter et al. 2020). In addition, Aurorasaurus conducts outreach and education across the globe, often through partnerships with scientific, photography, and aurora chasing groups. It engages the citizen scientists in activities such as reading journal articles, writing scientific papers, and conducting independent research, as well as more traditional outreach events and documentary film screenings.

Aurorasaurus is working to expand its community in the polar and subauroral regions, including via tourism in Norway and rural Alaska, as well as with Indigenous communities. The project has demonstrated that while scientific efficacy is traditionally gauged via

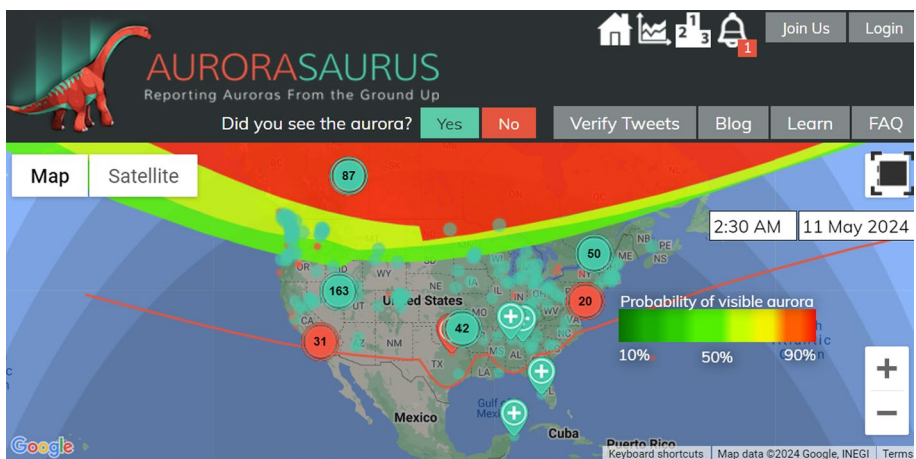


Fig. 3 Screenshot of the Aurorasaurus homepage during the May 2024 extreme geomagnetic storm at 6:30 UTC on 11 May 2024. Hundreds of positive aurora reports are seen (green) along with many negative aurora reports (red). The projected auroral view line (red line) is adjusted to account for ground-truth reports (Case et al. 2016a).

publications, the inherently interdisciplinary value of citizen science spans a broader range of goals and methods (Edson et al. 2024).

3 Emerging citizen science initiatives in heliophysics and atmospheric physics

3.1 Data collection by individuals

As was introduced in the previous section, citizen scientists can collect a broad range of data through observations they make, thus bearing potential for both making discoveries of new phenomena and carrying out statistical analysis of selected physical processes. Here we briefly review ongoing initiatives relying on data collection by individual observers to be uploaded to collaborative platforms and data banks.

Several citizen science initiatives relying on measurements made by individuals consist of providing the participants with either a simple instrument or an application to download on their smartphone. For instance, the Cosmic on Air project (<https://cosmic-on-air.org/>) is a citizen science project encouraging the public to collect radiation dose measurements onboard flights and making them available to the scientific community. Volunteers can get a dosimeter and carry it during their flights to collect data. These contributions, among other topics, support the identification and quantification of effects of solar flares on the lower atmosphere (Darley et al. 2019). These measurements can also be leveraged for characterising the Earth's radiation environment (Bottollier-Depois et al. 2019). Similar projects have relied on volunteers to collect atmospheric pollution data. For instance, in the city of Coyhaique in Southern Chile, the ExCamp project (<https://www.cr2.cl/finaliza-campana-cientifico-ciudadana-para-medir-calidad-del-aire-en-coyhaique/>) has organised several campaigns of air quality measurements involving citizen scientists who walked across their neighbourhoods carrying low-cost sensors during mornings, early afternoons, and evenings. In astronomy, the worldwide Globe at Night project involved thousands of citizen scientists from every continent (except Antarctica) who reported on naked-eye visibility of stars from their region. The collected data enabled quantifying the reduction in star visibility between 2011 and 2022 (Kyba et al. 2023).

An example of initiative making use of participants' smartphones is the collection of global navigation satellite system (GNSS) data. Low-cost GNSS receivers providing raw GNSS measurements with multi-constellation and multiple frequencies are nowadays found on a number of smartphones. The accessible data include GNSS time, pseudoranges, carrier phase measurements, Doppler shift, satellite ID, constellation ID and it can be logged by apps (e.g. Geo++ RINEX Logger). The data can be post-processed alike any other GNSS measurements (e.g. GSA GNSS; Tomaštk et al. 2024). While the quality of the measurements and their usability for different research areas vary, being able to collect such a vast amount of data by citizen scientists can still be beneficial for many applications. For ionospheric research, the co-use with a camera can identify whether aurora is present and whether positioning systems are disrupted by it. Recent articles and conference contributions have already started assessing the use of Android smartphones with dual-frequency multi-GNSS receiver to measure the total electron content and atmospheric parameters (Kogogin et al. 2021; Soja 2022; Williams et al. 2023). Collecting a vast amount of data via citizen scientists (crowd-sourced GNSS data) can provide great potential for statistical studies on ionospheric dynamics and impacts on positioning systems.

Smartphones have also been utilised as measurement devices for atmospheric pollution by aerosols. This was demonstrated via the development and testing of the iSPEX smartphone add-on, a low-cost element effectively transforming a smartphone camera into a spectropolarimeter (Snik et al. 2014). Three measurement campaigns were held in the Netherlands during summer 2013, during which several thousand citizen scientists participated, which enabled obtaining maps of aerosol optical thickness down to a spatial resolution of 2 km.

Another example is CrowdMag (<https://www.ncei.noaa.gov/products/crowdmag-magnetic-data>), a citizen science project by NOAA that uses smartphone sensors and the CrowdMag app to collect anonymised geomagnetic data. The primary goals include mapping Earth's magnetic field and local noise sources. The project supports scientific research by filling gaps in magnetic field data, especially in areas with sparse ground-based measurements.

For some physical phenomena, smartphones are however not advanced enough to collect the necessary data. In such cases, the projects target communities of passionate observers who have advanced equipment and strong expertise in chasing and capturing these phenomena. A first example is Spritacular (<https://spritacular.org/>), a NASA citizen science project that was launched in October 2022. The primary goal of this project is to collect observations of sprites and other optical phenomena occurring above the thunderstorms, collectively known as transient luminous events (TLEs). The Spritacular database includes TLE observations with metadata by extremely skilled storm chasers (mobilised sensors) from 15 different countries, producing a steady stream of valuable observations for the scientific community to work with. This database will be an invaluable resource for finding interesting cases, performing studies in conjunction with other scientific data, and conducting broad statistical studies. This project also aims to connect the public with scientists to ensure optimal exploitation of these data.

More examples can be found in auroral physics. A Canadian initiative named AurorEye, developed by Jeremy Kuzub at Jufa Intermedia (<https://auroreye.ca/>), is leading the development and deployment of portable all-sky imagers for aurora chasers to install in the field and autonomously capture timelapse images (Kuzub 2022). AurorEye provides calibrated timestamps and geolocation information associated with the images and comes with software to automatically generate and upload timelapse videos and keograms to a cloud server accessible by scientists. Sequences are also shared on the AurorEye YouTube channel for public viewing. AurorEye prioritises user-friendly design and operation: components are largely modular and off-the-shelf. A responsive development team means technical bugs or software glitches can be patched quickly or even by the operator. This is an example of an “agile” citizen science project (Ledvina et al. 2023).

The North Dakota Dual Aurora Camera (NoDDAC; Young et al. 2022) project, a collaboration between the University of North Dakota (UND), Aurorasaurus, and the Nueta Hidatsa Sahnish Tribal College (NHSC), is another example of an auroral imagery citizen science project. NoDDAC provides constant observation of rare mid-latitude auroral (or aurora-like) phenomena (e.g. STEVE, SAR arcs, dunes) through the use of a “dual” camera system consisting of a north-facing video and an all-sky still camera. The system is designed to be expandable and agile. The camera components are commercially available Sony cameras and IPTimelapse software controls the automatic capture, storage, and uploading of image sequences to an aurora dashboard (in development). Images from the north-facing video camera are livestreamed to the NoDDAC YouTube channel. NoDDAC has now expanded to two locations, unlocking the potential to triangulate the heights of STEVE and other rare phenomena. The project will soon be incorporated into

the Aurorasaurus project by means of providing aurora alerts to users through automatic aurora-detection algorithms. NoDDAC's companion Zooniverse project (see Sect. 3.1) will help categorise and identify the thousands of aurora images that have been captured since the project's inception in 2021.

Insightful observations of the aurora can also be provided by citizen scientists who do not take advanced instrumentation to the field, and even do not necessarily have extensive experience with aurora chasing. Since 2023, the ARCTICS working group sponsored by ISSI-Bern, Switzerland, has gathered together citizen scientists and researchers from various regions of the world to collaborate on the study of dark-sky optical emissions (aurora, STEVE, FAE, and others). The aim of the collaboration is not only to produce scientific research outputs but also to expand the network of citizen scientists in auroral studies, connect the communities together, and provide tips and guidelines for aspiring citizen scientists not necessarily having prior experience with participating in the scientific research process. To this aim, ARCTICS released the first version of an *Aurora Field Guide and Handbook for Citizen Science* (Herlingshaw et al. 2024) addressed to both citizen scientists and academics. The Handbook highlights how collaboration between citizen scientists and professional scientists is beneficial to both groups, who learn from each other. Very recently, during the Gannon/Mother's Day Storm which occurred in May 2024, the ARCTICS collaboration collected reports of aurora sightings by citizen scientists from all around the world via an online survey. The reports indicated that the auroral oval extended well beyond the NOAA G5 (extreme) storm description, with aurora spotted from latitudes as low as 30° (Grandin et al. 2024). Citizen science auroral observations also complemented the few available scientific optical observations by providing reports from high latitudes in the northern hemisphere where instruments were not running due to the lack of dark conditions in summer. With nearly 700 respondents to the survey – many of whom saw the aurora for the first time in their life – this study showcased the potential of collecting observations of specific events even when no dedicated observation campaign has been organised in advance.

Other studies of the Gannon/Mother's Day Storm have relied on citizen science observations from, e.g. Mexico (Gonzalez-Esparza et al. 2024) and Japan (Kataoka et al. 2024; Nanjo and Shiokawa 2024). More generally, over 5000 geolocated and time-tagged reports were also submitted to the Aurorasaurus platform. In the northern hemisphere, reports as far south as Oman and India highlighted the extent of aurora that could be detected with modern technology (e.g. cameras utilising long-exposure photography). As many reports also indicated naked-eye visibility, colours present, and included photos, Aurorasaurus has created a multidimensional dataset that can be used to study the rare superstorm in closer detail. On aurorasaurus.org, the view line extended across the southern USA and adapted to positive clusters of aurora reports in Texas and Florida (see Fig. 3).

Moreover, during this superstorm, several users reported disruption and malfunctioning issues. Among these, they reported negative effects on ground-based broadcasting and two-way radio communications, especially on the HF band because at the same time as the storm was ongoing, solar energetic particle events increased the D-region electron density in the polar ionosphere, causing absorption and thus loss of signal (e.g. Patterson et al. 2001). Figure 4 shows the HF radio signal absorption map predicted by NOAA/SWPC at 15:26 UT on 11 May 2024. It reveals unusually large absorption affecting the high latitudes, especially in the northern hemisphere, with an extension to regions seldom affected by such disturbances (southern Fennoscandia, Denmark, UK, southern Canada), which is likely due to the precipitation of solar energetic particles (Heino and Partamies 2020). In addition, strong X-ray flux associated with the peak flux

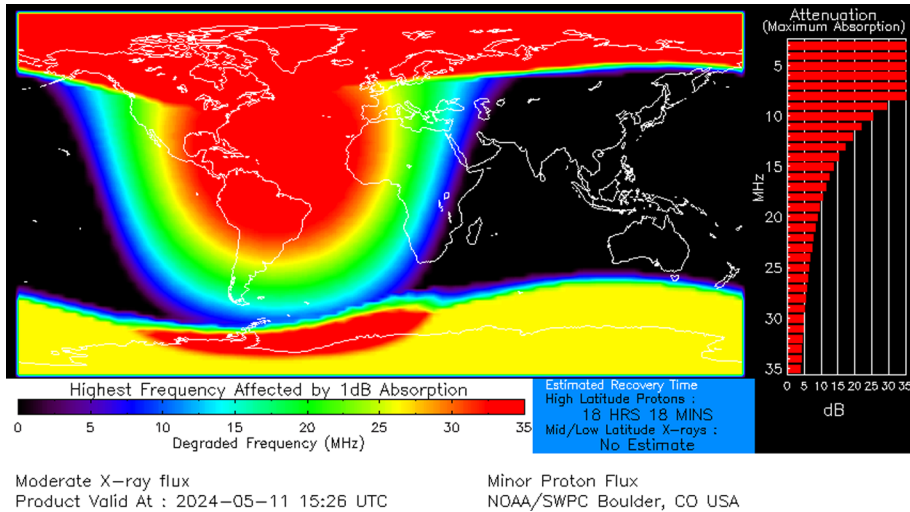


Fig. 4 Map of HF radio signal absorption at 15:26 UT on 11 May 2024 produced with the D-Region Absorption Prediction model. The colour scale gives the highest radio frequency undergoing 1 dB absorption in the lower ionosphere.

of an M8.8-class solar flare which started at 14:46 UT (e.g. Hayakawa et al. 2025) led to HF signal absorption at lower latitudes located on the dayside of the Earth. This is consistent with a report by WSPRNet (see Sect. 2.2) on radio propagation conditions in the US sector during the event, stating that “No receiver reports at all were received, on any band, between 2100 UTC 10 May and 0000 UTC 12 May” (WsprDaemon group 2024). In addition, in the European sector, radio amateurs in central Italy reported (via personal communications) to the scientists from the Istituto Nazionale di Geofisica e Vulcanologia (INGV) the impossibility to establish HF radio links at 10, 12 and 15 MHz on 11 May 2024, as INGV had been communicating via social media about the event (Spogli et al. 2024). The example of the May 2024 superstorm illustrates how exceptional events can provide great opportunities to leverage citizen science to complement observations from scientific instruments.

A month earlier, another rare celestial event offered a great opportunity to engage the public in citizen science. During the total solar eclipse of 8 April 2024 across the North American continent, several citizen science projects have been collecting data, to study both the Sun and the response of the Earth atmosphere during the eclipse. This event was hence an excellent opportunity to promote several citizen science project and to involve the general public in observations and science. In particular, one can mention some of those projects, several of which are reflecting the possibility to also involve volunteers in the analysis of the data collected:

1. In the Citizen CATE 2024 project (Seaton et al. 2024, <https://eclipse.boulder.swri.edu/citizen-cate-2024/>), a network of volunteer teams were equipped and trained in advance to capture videos of the solar corona during the eclipse.
2. The Dynamic Eclipse Broadcast (DEB) Initiative (<https://debinitiative.org/>) trained volunteers in advance and provided equipment to conduct coordinated observations of the Sun during the eclipse.

3. The Eclipse Megamovie project (Hudson et al. 2021, <https://eclipsemegamovie.org/>) collected photographs of the eclipse in order to study dynamic features in the solar corona.
4. The SunSketcher project (Severino et al. 2025, <https://sunsketcher.org/>) can be seen as the modern version of one of the earliest citizen science initiative, during the total solar eclipse observed in England in 1715 (Halley 1715): for this project, anyone who downloaded the dedicated application on their smartphone could take data during the eclipse to precisely measure the timing of the observations of the Baily's beads, i.e. the last and first glimmers of sunlight before and after totality.
5. Observations of the eclipse were also conducted in the radio domain, by volunteers who had assembled their own radio receivers, for the Radio JOVE project (<https://radiojove.gsfc.nasa.gov/>). Radio emission can also be used to study the impact of the eclipse on the Earth atmosphere, as it was done by amateur radio operators participating in HamSCI (see Sect. 2.2), to study the properties of the ionosphere. This project is also running outside of solar eclipses.
6. Another long-running project, GLOBE Observer (<https://observer.globe.gov/>), carried out a specific campaign during the eclipse to record air temperature and cloud cover.
7. Eclipse Soundscapes (Hartstone-Rose et al. 2024; Severino et al. 2025, <https://eclipseoundscapes.org/>) was dedicated to the recording of sounds during the eclipse, with prior training of the volunteers to acquire the data.

3.2 Hosting instruments in non-scientific public structures

For some projects, relying on networks of individuals may not be the most suitable approach to collect observations. Rather, having scientific instruments hosted by public structures can prove an effective way to not only collect observations but also facilitate the maintenance of the instrument and engage specific parts of society in the project – in particular schoolchildren.

NASA's Electrojet Zeeman Imaging Explorer (EZIE) mission will consist of three small satellites aiming to describe the auroral electrojets in detail (<https://ezie.jhuapl.edu>). In addition to the flying platforms the mission includes mass-produced ground-magnetometer kits called EZIE-Mags (<https://ezie.jhuapl.edu/outreach/ezie-mag/>) that are being distributed to schools in the USA to inspire and include young people in the data collection for part of the mission (Gjerloev et al. 2024). However, anyone in the world can apply for an EZIE-Mag. The lunchbox-sized kits are simple to deploy and all necessary data processing, such as baselining, is done as post-processing. All EZIE-Mag so-called beta testers were strongly encouraged to run their magnetometers during the Gannon/Mother's Day Storm on 10–13 May 2024 and upload the data for science analysis. Ground magnetic field data recorded by EZIE-Mags operating during the Gannon Storm are available on the mission EZIE-Mag website (<https://eziemag.jhuapl.edu/gw/>).

All-sky-cameras have long been a part of atmospheric research. These cameras have typically been installed to measurement stations of scientific organisations, but an alternative approach involving local schools is being tried in Finnish Lapland by Sodankylä Geophysical Observatory. Each school participating on Revot-project tries to locate a nearby dark spot for their camera instrument, run it and, as a reward, gains access to the collected image material. The project is aiming to raise interest towards natural sciences and underline the importance of the rare areas where the night sky is still dark.

Weather is something we all face every day. However, the available data from the official weather stations and the operational numerical weather forecasts do not always reflect the local variability in a comprehensive way. This is particularly true in remote locations surrounded by mountainous topography and ocean, where observational data are typically sparse and weather prediction models often struggle. To improve coverage of weather observations and to facilitate development of better weather models, a local network of Netatmo Smart Weather Station kits (<https://www.netatmo.com/en-gb/smart-weather-station>) is being beta-tested in Svalbard, Arctic Norway. The weather stations are run on local wireless network connections that automatically take care of the data collection and distribution to large-scale weather map (<https://weathermap.netatmo.com>). The Svalbard project, called LongyearObs (<https://www.longyearobs.com>), investigates a way to harvest the individual weather station data into a science database for further analysis. A main aim in this project is to standardise the outdoor stations' setup so that the biases due to, for instance, proximity of buildings can be avoided.

Perhaps the most successful and longest-running severe-weather-related collaboration project between scientists and citizens is the Blitzortung station network, that has been in operation since 2005. It consists of more than 1500 currently running VLF radio receiving stations worldwide and related data processing systems. These lightning detection stations are mainly run by amateurs, who by participating gain access to the raw data gathered by the network. Part of the collected data are openly available for various purposes of which the map visualisation at <https://www.blitzortung.org> is the most widely used. The receiver technology is continuously being improved and device purchase costs optimised towards low-cost solutions.

Another ongoing effort to involve public structures in hosting instruments is the deployment of low-cost Ku-band ozone radiometers. Traditional radiometers are expensive and require skilled scientists, limiting widespread use and public involvement. However, the low-cost radiometer developed by Rogers et al. (2009), called the 'Mesospheric Ozone System for Atmospheric Investigations in the Classroom (MOSAIC)', offers a solution. Sodankylä Geophysical Observatory is improving this system to enhance data quality and achieve daily temporal resolution while keeping costs low and instrument stability. By involving more high schools and universities in deploying these instruments, the project promotes education and provides valuable, stable ozone data, particularly in polar regions where data gaps exist. Due to the COVID-19 pandemic, the radiometer has been maintained at the observatory instead of being deployed in high schools or universities. However, it is expected that the long-term MOSAIC ozone data will serve as valuable scientific data for mesosphere–lower-thermosphere ozone research and help understanding the coupling between the thermosphere, mesosphere, and stratosphere.

The Space Weather Underground (SWUG; Smith et al. 2019) programme was created by Charles Smith as a collaborative effort between University of New Hampshire (UNH) and high schools in northern New England. The goal of this programme is to build and deploy a network of magnetometers to better characterise the ionosphere and investigate geomagnetically induced currents (GICs) while at the same time educating and inspiring students about space weather. High-school students build and test the magnetometers, which are then deployed at or near the high school, and UNH collects and processes the resulting data. The data are then made freely available to the public. In 2020, the SWUG programme expanded to University of Alaska Fairbanks (UAF, Cohen et al. 2021; Ozturk et al. 2023) to evaluate the significant threats to infrastructures in high-latitude regions like Alaska. The UAF SWUG programme developed a free 2-week intensive summer course for secondary-school science teachers. As a part of this course, educators learn about space

weather, how to build and deploy magnetometer kits, and how to analyse magnetometer data. UAF then provides support for these educators to begin SWUG programmes at their own schools. High-school students can also work directly with the UAF SWUG team at any time of the year. Students spend at least 3 h per week assembling a magnetometer and assisting its calibration and deployment. Recently, UAF SWUG added low-cost all-sky cameras (developed by Frank Prins) to its training programme and deployed instruments, offering the opportunity to monitor various auroral conditions through imagery. Similar to UNH, UAF makes all camera and magnetometer data publicly available along with educational material and manuals. In 2022, the University of Maryland began its own SWUG programme (MD-SWUG; Connor et al. (2024) with a similar programme to the UNH SWUG initiative. MD-SWUG specifically targeted investigating the effects of the annular and total solar eclipses of 2023 and 2024, respectively, using student-built magnetometers.

3.3 Data processing by citizen scientists

While the ongoing projects discussed in the earlier sections focus mainly on data collection, there are other ways to involve the public in the scientific process in the contributory framework. A great number of initiatives have been flourishing concerning the inclusion of citizen scientists in data processing. Among these, a noteworthy platform is Zooniverse (<https://www.zooniverse.org/>), which claims over a million volunteers who actively contribute to scientific research by carrying out various kinds of tasks in a wide range of fields. Among those volunteers, a small number of particularly active members show an engagement which can be considered to belong to the collaborative typology, while the majority of the participants are rather involved within the contributory framework (Krukowski et al. 2022).

An example of a recent Zooniverse project, AtmosElec (<https://www.zooniverse.org/projects/hripsi-19/atmoselec-atmospheric-electricity-for-climate>) aims to utilise citizen scientists to help digitise many decades of atmospheric electricity data from Lerwick Observatory, UK. Atmospheric potential gradient measurements were made from this site from 1927–1984, originally in handwritten tables, and now digitally scanned. This is one of the longest continuous time series of potential gradient measurements in the world, and digitising such a valuable dataset is expected to lead to insights into how atmospheric electricity is linked to climate processes, as well as how space weather controls atmospheric electricity.

Zooniverse projects can also be well-suited for the analysis of complex data from heliophysics missions. For instance, Solar Dynamics Observatory (SDO) launched by NASA in 2011 produces images of the Sun at different wavelengths at unprecedented time cadence and spatial resolution, which triggered the development of algorithms for detection and classification of features seen in the data. However, not all analysis can be automated, due to the complexity of the data or of the tasks: this is where citizen science is the best methodology. The Solar Jet Hunter (<https://www.zooniverse.org/projects/sophiemu/solar-jet-hunter>; Musset et al. 2024) and Solar Active Region Spotter (<https://www.zooniverse.org/projects/eimason/solar-active-region-spotter>) both ask the volunteers to analyse data from SDO. Earlier examples based on different heliophysics missions include Solar Storm-watch (<https://www.zooniverse.org/projects/shannon-solar-stormwatch-ii>), where volunteers were marking images from the coronagraphs onboard the Solar Terrestrial Relations Observatory (STEREO) probes during coronal mass ejections (CME) to track their evolution. More than 100 CMEs have been tracked via this project (Barnard et al. 2014).

Although not hosted by Zooniverse, an exciting project in the same field is Heliophysics Audified: Resonances in Plasmas (HARP), where the volunteers are presented with audified versions of plasma waves measured with the THEMIS mission in order to identify resonances (Archer et al. 2018, 2022).

Coming to auroral physics, the Zooniverse “Aurora Zoo” project focuses on fine-scale aurora (scale sizes of tens of metres to a few kilometres). Fine-scale aurora is not often accessible to citizen observers due to the equipment required for clear observations, such as sensitive detectors and optical filters that exclude the long-lived emissions which can appear smeared on fine scales. Citizen scientists contribute to Aurora Zoo in two main ways: by classifying short video clips of the aurora made using the ASK instrument according to the structure and dynamics present (enabling statistical studies of fine-scale aurora), and by spotting unusual things present in the data set. This combination of making classifications and reporting unusual features is common to many projects on the Zooniverse platform. As of June 2024 more than 700,000 classifications have been made of 71,209 clips using a classification scheme devised by the Aurora Zoo project scientists, comprising 6 shapes and 6 movement classes together with an indication of how diffuse the aurora appears. In addition, the Aurora Zoo volunteer community has developed a list of “tags” which can be applied to clips to highlight more unusual features, such as flaming auroral rays (Cresswell 1969) and ruffs (Dahlgren et al. 2010). The tags are attached to clips in posts on a discussion forum incorporated within the project. This feature can function in a similar way to citizen scientists making, reporting and analysing their own observations, and was used to discover a FAE event present in the data and analysed by Whiter et al. (2021, see Sect. 2.4). Other projects of auroral image classification by citizen scientists exist, such as AuroralZone (<https://auroralzone.org/>) led by the University of Calgary (Canada).

4 Challenges to overcome

4.1 Citizen scientist engagement and training

The successful implementation of citizen science initiatives is filled with several challenges that must be addressed to maximise their effectiveness and reach. It is crucial to create comprehensive and detailed instructions for tasks given to citizen scientists. It is important to consider that volunteers come from various backgrounds and need clear, precise instructions (and in some cases even training, for instance via videos) on how to contribute to projects. Ensuring that these instructions are easy to follow is essential for maintaining continuous engagement, as well as mitigating errors and improving the quality of the data obtained (see also Sect. 4.2). Revisiting these instructions, requesting feedback from participants, and acting on that feedback is also beneficial to the success of citizen scientist projects.

Citizen scientists have innate scientific agility (Ledvina et al. 2023). This means they can provide both contributory and experiential expertise. Key to the success of citizen science initiatives is realising the skills of participants and integrating them across as many steps of the scientific discovery process as possible. This may include inviting participants to help with reviewing papers before submission to journals and inviting community leaders to scientific conferences. At the bare minimum, citizen scientists must receive reciprocity for their efforts through acknowledgement and ideally co-authorship in scientific

publications and presentations. While gamification elements (e.g. awarding participants with badges or certificates) are fun and low-effort ways to retain participation from volunteers, more concerted efforts to engage citizen science communities will earn their respect and retention. Citizen science is community science; project leaders should prioritise leaving “deposits” that create tangible benefits in the communities they engage with. For example, in exchange for participants reporting auroras on their site, Aurorasaurus also leads an ambassador network which engages aurora chasing community leaders with scientists and subject matter experts. Public talks and outreach events, a monthly newsletter, an early-career group, and a regular blog articles are all other ways in which Aurorasaurus engages and adds value to the aurora chasing community.

Another significant challenge is the promotion of the citizen science project to engage a wide audience. Nowadays, the question of language barrier, which can limit the diversity of participants, has become less critical thanks to the availability of automatic translation software. Reaching potential citizen scientists across socioeconomic backgrounds can however be more challenging. In this, effective communication strategies are essential, including the use of social media, blogs, and dedicated websites to advertise projects. Writing compelling articles, issuing press releases, and conducting interviews are vital components of a successful outreach campaign. Portas et al. (2016) discuss their use of different communication vehicles for their NEWEx citizen science project which collected data on the partial solar eclipse over the UK in 2015. For this they utilised pre-existing distribution lists from societies such as the Institute of Physics and the Royal Meteorological Society, engaged directly with media outlets such as the BBC to advertise the project to school children, and organised a series of lectures and open days to encourage local participation. These efforts help to raise awareness about projects and their goals, ultimately driving participation. Initial analysis of participant numbers in the AtmosElec Zooniverse project have shown a clear correlation between media engagement activities and increases in the number of citizen science volunteers, demonstrating the importance of continued efforts in this area.

Finally, citizen science projects can be difficult to maintain over a long period of time. Some projects have shown exceptional longevity: the ham community can boast a century of contributions to atmospheric and space sciences (see Sect. 2.2), and the Skywarden observation platform has been continuously developed and maintained for over a decade and includes digitised versions of past observations from the second half of the 20th century. Both examples rely on extremely active – and often highly skilled – communities who have invested time, money and energy to purchase equipment (e.g. radio transmitters in the case of ham), build their network of participants, develop online tools for communication and data management, and moderate the discussions and data submissions. However, not all citizen science projects can reach such a level of engagement, which can be qualified as professional by many standards, making it challenging to sustain them in the long run. Projects primarily having an outreach component, like those involving schools, are therefore often shorter-lived, as the involved participants (staff and students alike) have a relatively fast turnover. Likewise, data collection projects in which a certain number of measuring devices are distributed to citizen scientists are likely to have their longevity tied to the lifetime of the equipment, in the absence of funding to replace the instruments when they cease to function.

4.2 Management of citizen science data

Whether it relies on science-grade-instrument or citizen science data, a scientific study requires that data quality is guaranteed. While scientific instruments are typically calibrated in laboratories and the produced data undergo validation through established procedures, calibration and validation of citizen science data is less straightforward. Downs et al. (2021) stress the importance of assessing and documenting the data quality in citizen science projects, encouraging citizen science project leaders to consider quality assessment and quality control early on in the project, ideally during the stage of conceptualisation of the study. They describe four stages in the lifecycle approach to citizen science data quality, as previously introduced by Ramapriyan et al. (2017): (i) scientific quality (from data definition to validation); (ii) product quality (from data set production to its distribution and archiving); (iii) stewardship quality (maintenance, preservation and dissemination of the dataset); and (iv) service quality (facilitation of data reuse, user support).

The scientific quality of citizen science data, in particular, can be boosted by several means, as suggested by Kosmala et al. (2016). First, as already discussed in Sect. 4.1, the project leaders can invest time and effort in training the citizen scientists to perform their tasks (which can be collecting samples, making measurements with a specific device, or identifying certain features or phenomena); this reduces the risk of human errors. Second, the measuring devices operated by citizen scientists can be standardised and calibrated; this reduces instrumental errors. Third, implementing a replication of measurements by several citizen scientists or a cross-calibration procedure can improve the reliability of image classification, for instance, by reaching consensus. Fourth, similar statistical methods as used with science-grade-instrument data can be applied to the citizen science data to reduce the uncertainty, such as increasing the number of samples, or applying a skill-based statistical weighting of the classifications or measurements. When the above methods are adopted in citizen science projects, Kosmala et al. (2016) argue that the scientific quality of the citizen science datasets can be on par with those coming from science-grade instruments.

More generally, Balázs et al. (2021) highlight that data quality, i.e. the validity and reliability of the data, is one of the four aspects pertaining to their broader concept of *data accuracy*. The other three aspects are: data contextualisation (which includes the metadata and the description of the protocol and methods employed in the data collection), data interoperability (how the data and their processing can be used in a different project from the technical point of view), and data reuse (in terms of ownership and future accessibility). Hence, the management of citizen science data needs to be carefully considered. Data management requires education and planning, both on the scientists' and citizen scientists' side. Determining how to collect and publish citizen science data depends, among other things, on the project's planned time frame and budget, as well as on local legislation. Setting up a data management plan – and updating it as necessary – is paramount to avoid caveats during the project. Overall, one should adhere as much as possible to the FAIR data principles (Wilkinson et al. 2016).

Citizen science data nevertheless come with specific challenges, at the same time as they create new opportunities. One example can be found in atmospheric physics, for which access to long-term time series of data has a critical role when monitoring development and trends. Since many citizen science projects target one particular research question at the time, the time span of observation campaigns is often limited to a single period or event. However, it is not uncommon to rediscover older data coming from past citizen science campaigns and that could prove insightful if combined with more recent observations.

Figure 5 shows an example of auroral observations made by Finnish volunteers during the IGY (see Sect. 2.1), recently rediscovered from the FMI archives. The existence of such observations from before optical instruments for auroral studies were common suggests that there may be an unused potential in revisiting old datasets. This argues in favour of long-term data collection, provided that methods for intercalibration of data from one campaign to another are devised. Getting appropriate commitment and funding for running long campaigns, or developing such intercalibration methods, is a common issue in building reusable data sets covering long time periods.

Another issue is the question of ownership of the citizen science data. For instance, in auroral studies relying on citizen science imagery, clarifying whether a photographer retains their copyright when uploading their pictures to collaborative databases or whether the images fall into the public domain is paramount. In the ARCTICS Aurora Handbook for Citizen Science (Herlingshaw et al. 2024, Sect. 9.3.4), the authors strongly recommend systematically adding a licence to the uploaded images or videos. In case an auroral photograph is published in a scientific article, the citizen scientist owning the copyright should be consulted when determining the licence for the publication. Beyond ownership as defined by copyright, the wider notion of credit attribution is further discussed in the ARCTICS Handbook.

In addition to data ownership, data management also involves identifying the data controllers. In citizen science projects, the role of data controller may be shared between the academics and the citizen scientists, especially in collaborative and co-created projects. This may raise issues such as making citizen scientists jointly responsible for the data management and protection together with the academics, whereas they are often not knowledgeable on such legal aspects (Purtova and Pierce 2024).

Half-sky auroras - 24.3.1958 at 22.50 Iisalmi

Observation number 126691



Visibility IV / V
Tauno Laajalahti

I am sending this drawing of the aurora borealis, which were very strong last night (March 24, 1958) at about 22:50 SA, which time the drawing mostly represents. A bright narrow belt stretched from the moon through Andromeda to below Vega, which was completely red near the moon, continuing pale yellow past Andromeda and clearly greenish near the constellation Swan.

From Andromeda to Cassiopeia, the sky was pale yellow over a wide area, and only the brightest stars could be distinguished from that area. Near Andromeda and Betelgeuse, the sky was uniformly orange.

Above the Cygnus constellation and in the regions of Arcturus, the sky was slightly greenish-yellow, but very bright. There was a small orange area between them. In all the above-mentioned places, the aurora borealis was visible evenly.

Instead, in the middle sky, they fluttered, forming a fold in the vicinity of Otava. A little below that was the southern edge of the northern lights.

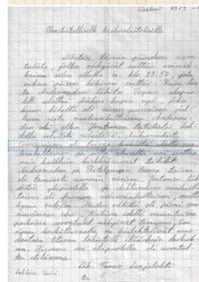
Cartoon: The northern lights were at their strongest at around 22:50. Around 23:45, only the belt marked in the picture was visible, very dim and irregular.

Original material: Tauno Laajalahti (Iisalmi) 25 March 1958, Meteorological Institute (IL) archive. Northern lights photography is related to IL's International Geophysical Year (IGY) 1957–1958 public aurora observations collection project.

H. Nevanlinna and E. Bruus

✓ This description has been automatically translated from Finnish. [Click here to see the original text.](#)

[More similar observations](#)



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Fig. 5 Screenshot of the Skywarden observation number 126691 from 24 March 1958 by Tauno Laajalahti, from Iisalmi, Finland. The observation was part of the IGY campaign involving volunteer observers who reported on aurora sightings (see Sect. 2.1). The original material (left), recently rediscovered from the Finnish Meteorological Institute archives, consisted of a letter in Finnish and a drawing of the observed auroral forms. An English translation of the texts is given on the right.

4.3 Interfacing of the academic and citizen scientist communities

Another challenge for citizen science to work out smoothly arises from the human aspects. Academics and citizen scientists come from different communities, each characterised by its own unwritten rules, aspirations, expectations. An intrinsic opposition between these communities, when it comes to participating in citizen science projects, is time: while for academics such endeavours are part of their working time, for citizen scientists the corresponding hours are generally part of their leisure time. This creates a double challenge. First, academics cannot expect from citizen scientists more time dedication than they are willing to provide, given that it is voluntary (and hence unpaid) work from their part. Second, citizen scientists need to understand that academics also need to maintain their work–life balance and cannot always be reactive to solicitations and enquiries, especially outside of their working hours. The solution to this double challenge can be found in transparent communication of boundaries from each party and a mutual understanding of each other's constraints and needs. The *ARCTICS Aurora Handbook for Citizen Science* (Herdingshaw et al. 2024) includes suggestions to overcome these issues.

Adjacent to the above issue is that of determining the suitable platforms for communication between academics and citizen scientists. While emails are the natural solution for keeping interactions at the professional level, chat-based solutions such as offered by the social media platforms may be preferred on some occasions, as they foster more interactive and spontaneous discussions. However, they tend to blur the boundary between professional and personal life and therefore need to be used with caution. More generally, finding the right balance between professional and personal life, setting boundaries and navigating the differences is paramount to ensure not only a successful collaboration from the scientific perspective but also a fair and healthy relationship between academics and citizen scientists.

Overcoming such challenges can be greatly facilitated by involving citizen science coordinators and science engagement/communication specialists who can be the bridge between academics and citizen scientists. Thanks to their education and experience working with both professional and citizen scientists, they can be an essential asset in managing citizen science projects efficiently and smoothly. Science outreach organisations (such as museums) and educators in schools can also support these aspects by bringing in the needed skill set. Naturally, this is contingent on funding, which can be another challenge for citizen science.

4.4 Funding citizen science

Citizen science projects can be funded as any other scientific project by funding agencies, covering campaign costs, salaries of academics working on the project, and travel money for them to attend and present results at conferences. NASA, for instance, has dedicated funding opportunities that include a citizen science component (see <https://science.nasa.gov/citizen-science/resources/>). However, funding citizen scientists themselves to participate in conferences or workshops can be a challenge. Research institutes have varying rules regarding the reimbursement of travel costs for conference participants not employed by them, which means that even when travel money has been set aside for citizen scientists, it may be cumbersome to get their travel expenditure covered by project money in practice. When a research institute has a straightforward process to cover the travel expenses

of guests as long as the purpose of the trip is aligned with the institute's goals, it can be an incentive for citizen scientists to collaborate with researchers and a way to reward their engagement by enabling them to participate in the scientific dissemination.

Additionally, because citizen scientists contribute to the science on a voluntary basis, they often need to make special arrangements with their employers or take annual or unpaid leave to attend conferences and workshops. This can involve making sacrifices not only from a financial perspective, but also in terms of private life. While the latter cannot be compensated for, it would be highly desirable to find ways to limit the effects of the former, by devising specific funding schemes for citizen scientists who present the research they contributed to and get exposure to the adjacent scientific progress during conferences.

Another excellent example of citizen science engagement is the NSF-funded STEVE workshop. This initiative has created a platform for meaningful collaboration between researchers and citizen scientists. By utilising NSF funding to support travel for both groups to the annual event, it has fostered valuable partnerships that have sparked new and thriving research (e.g. Martinis et al. 2022; Nishimura et al. 2022; Gallardo-Lacourt et al. 2024). Expanding initiatives like this across the broader scientific community could greatly enhance scientific discovery, as this model has proved to be an effective avenue for innovation.

A last point that can be raised regarding the funding of citizen science is the question of offering a financial compensation for citizen scientists' work. This is a complex issue involving ethical, legal, and practical considerations, with no straightforward answer. This topic is to a great extent beyond the scope of our paper whose aim is to focus on citizen science in atmospheric and space physics. Nevertheless, we note that this issue is discussed in articles on research ethics, for instance with respect to the risk of leading to human exploitation (Riesch and Potter 2014) or a decrease in public funding of research (Vohland et al. 2019) when the citizen scientists perform tasks that would have otherwise been carried out by paid scientists. Some citizen science projects have involved offering a financial compensation to the participants and argued that this had played a role in the motivation for citizen scientists to undertake data collection (e.g. Alizadehtazi et al. 2022; Larson et al. 2016). It is then a philosophical question whether participants who are paid for collecting data are best defined as citizen scientists or whether they de facto better fit the notion of employees of the project, with the project leaders outsourcing the data collection to them (Vohland et al. 2019). One may further argue that reducing the motivations of citizen scientists to monetary incentives does not do justice to the intrinsic interest in contributing to the advancement of scientific knowledge or in learning about nature through participation in a research project. In fact, there is a wide range of reasons why citizen scientists might be volunteering their time, also including seeking personal growth and fulfilment, having fun, contributing to something important, becoming part of a community, exploring a new career path (Lofian et al. 2020), pursuing one's passion in areas such as learning, nature and photography (Tolbert et al. 2024), or improving one's physical or mental health (Oh et al. 2025). And perhaps the beauty of citizen science is that it can bring together individuals from very diverse backgrounds and with different motivations, who collectively contribute to the advancement of science and knowledge. The existence of multiple realities within citizen science therefore makes it difficult to form a definitive opinion on the relevance of giving a financial compensation to citizen scientists in general.

5 Game-changing opportunities for citizen science

As technological progress opens new opportunities for science in general, it also creates new avenues for citizen science, accelerating its growth. Technological progress includes advances both in software (e.g. artificial intelligence) and hardware (e.g. miniaturisation of components). In addition to technological progress, other emerging initiatives to engage the public in citizen science include the collection of data during touristic activities, under the supervision of eco-tourism companies.

With the recent developments of the use of machine learning applications in science, the question of the validity of using citizen science for data analysis (such as discussed in Sect. 3.3) might be raised. However, there are fundamental differences between human and artificial intelligence which make the two approaches highly complementary. Algorithms will indeed be more efficient than citizen scientists in performing the task they have been trained for, but they will not be able to deal with unusual data or low-confidence results in a sensible way. In contrast, human volunteers are particularly good at spotting unusual features and making serendipitous discoveries.

Overall, citizen science can improve machine learning models in several ways. First, in order to train an algorithm, a training set is needed. Most of the time, labelled training sets are preferable, so a citizen science project in which the data set is labelled by the volunteers can provide a training set to be used as input to a machine learning project. Second, citizen science can be a key component of an active learning loop, the citizen science project being used to validate the results of the algorithm and to manually classify the low-confidence data resulting from the algorithm. This was demonstrated for instance by Zevin et al. (2024) in the citizen science project Gravity Spy. In the Galaxy Zoo project, the model was trained from the volunteers classifications to predict which galaxies would benefit from being examined by the volunteers, thus significantly reducing the volunteers' workload (Walmsley et al. 2020). Finally, in instances where the algorithm has been trained with unlabelled data (unsupervised learning), citizen scientists can examine the results and label clusters found by the algorithm. The combination of unsupervised learning and citizen scientists manual labelling has been employed by Wright et al. (2019) and demonstrated a significant reduction of the effort from the volunteers. In summary, the development of the use of machine learning in space science can be boosted by the use of citizen science to create the appropriate training sets, while trained algorithms will perform the most repetitive tasks faster and leave the more complex and interesting analysis to the care of the citizen science volunteers.

From the hardware perspective, the miniaturisation of electronic components makes it possible to produce portable and low-cost measuring devices capable of making measurements with sufficient reliability and accuracy to collect data for scientific use. Examples of such devices include the NoDDAC and AurorEye cameras (see Sect. 3.1) and the EZIE-MAG and SWUG magnetometers (see Sect. 3.2).

Besides the opportunities offered thanks to the most recent technological improvements, another way of engaging the public in citizen science has been the integration of data collection as part of touristic activities. While not yet concerning the fields of space physics and atmospheric sciences, one can mention the example of companies offering aurora-watching tours which include contributions to citizen science projects. For instance, in Northern Norway, aurora-watching and hiking tours offered by several companies such as Wandering Owl and Wild Lab Projects actively market the participation in citizen science data collection as one of the highlights of the experience. Adapting such initiatives to the

collection of data relevant to space physics (e.g. aurora photographs) and atmospheric sciences (e.g. meteorological observations) could be a future avenue for the application of citizen science in these fields. This would call for tourism operators to collaborate with data collection platforms such as Skywarden for the data management aspects, and with researchers for the formulation of needs in terms of data to be collected.

6 Closing words

In this overview paper, we have seen how citizen science has a long history in the studies of atmospheric and space phenomena, and how in the last decade it has gained renewed interest, with a great number of initiatives and innovative ways of engaging the general public in scientific research.

While the focus in this paper has been tuned mostly on recent initiatives, some communities have been active for decades and have kept collecting data even after the first projects around which they formed ended. For instance, an active community of citizen satellite observers is still present today, with communication facilitated by an email list (<https://www.satobs.org/seesat/seesatindex.html>). However, at the moment there is no active programme anymore to use their observations for upper atmosphere research. One possible reason for this might be that new techniques, such as based on GNSS data analysis (van den IJssel et al. 2020), have been developed to reliably infer thermospheric density nowadays. Nevertheless, it is not impossible that new applications of citizen scientist observations of satellites and reentry objects could emerge in future. Therefore, a renewed engagement between satellite observers and scientists studying the upper atmosphere is an example of avenue which could prove beneficial.

We have also discussed several of the challenges inherent to citizen science, such as maintaining the engagement of citizen scientists, providing them with training, ensuring the quality of citizen science data and managing them, interfacing the academic and citizen scientist communities, and funding citizen science. Addressing these challenges is important to bring citizen science to its full potential, which calls for sharing lessons learnt among academics and across the various communities (from both topical and geographic perspectives).

To conclude, we leave the reader with two take-home messages which are, in our view, crucial to create conditions for fruitful and pleasant collaboration between academics and citizen scientists:

1. Citizen scientists are collaborators who collect data and contribute valuably to data analysis. Citizen science project leaders need to know how to effectively recognise and utilise the many varied talents, skills, and interests volunteers possess.
2. Citizen scientists come to the projects with varying levels of expertise. Some may be very new, have limited experience, and will benefit from focused mentoring and training. Others may be retired with years in academia, industry, or other. They may be ready to hit the ground running and provide leadership or solve complex problems.

From the early auroral observation reports meticulously compiled by volunteers and mailed to researchers in Northern Europe during the nineteenth century (Sect. 2.1), through the contributions of highly skilled radio amateurs in the ham community that keep refining our understanding of the ionosphere (Sect. 2.2), to the recent discoveries of STEVE, the

dune aurora, and other dark-sky emission phenomena (Sect. 2.4) as well as the emergence of collaborative classification platforms such as Zooniverse (Sect. 3.3), citizen science has a long history of making significant contributions to atmospheric and space physics. Thanks to the rapid progress in machine learning and the development of low-cost and portable devices (Sect. 5), together with the ever-growing connectivity of society, citizen science is now entering a new era – one that foreshadows further advances and unexpected discoveries.

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Data Availability The citizen science reports of aurora shown in Fig. 1 are available in Grandin and ARCTICS collaboration (2024). The VIIRS Day Night Band image was sourced from the CIMSS Satellite Blog (<https://cimss.ssec.wisc.edu/satellite-blog/archives/59112>, last access: 17 April 2025). Additional VIIRS data can be found via the CIMSS VIIRS Imagery Viewer (<https://cimss.ssec.wisc.edu/viirs/imagery-viewer/>, last access: 17 April 2025).

The D-Region Absorption Prediction model map for 11 May 2024 shown in Fig. 4 has been obtained from NOAA/SWPC (<https://www.ngdc.noaa.gov/stp/drap/data/2024/05/>, last access: 17 April 2025).

The Skywarden observation shown in Fig. 5 can be accessed from its URL: <https://www.taivaanvahti.fi/observations/show/126691> (last access: 17 April 2025).

Declarations

Conflict of interest MG and NP are Guest Editors of the Special Issue to which this article is submitted.

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References

- Alizadehtazi B, Woerdeman S, Tangtrakul K, Gussenhoven A, Mostafavi N, Montalto FA (2022) Recruiting, paying, and evaluating the experiences of civic scientists studying urban park usage during the beginning of the COVID-19 pandemic. *Front Sustain Cities* 4. <https://doi.org/10.3389/frsc.2022.709968>
- Archer MO, Hartinger MD, Redmon R, Angelopoulos V, Walsh BM (2018) First results from sonification and exploratory citizen science of magnetospheric ULF waves: Long-lasting decreasing-frequency poloidal field line resonances following geomagnetic storms. *Space Weather* 16(11):1753–1769. <https://doi.org/10.1029/2018SW001988>
- Archer MO, Cottingham M, Hartinger MD, Shi X, Coyle S, Hill E, Fox MFJ, Masongsong EV (2022) Listening to the magnetosphere: How best to make ULF waves audible. *Front Astron Space Sci* 9:877172. <https://doi.org/10.3389/fspas.2022.877172>
- Balázs B, Mooney P, Nováková E, Bastin L, Jokar Arsanjani J (2021) Data quality in citizen science. In: Vohland K, Land-Zandstra A, Ceccaroni L, Lemmens R, Perelló J, Ponti M, Samson R, Wagenknecht K (eds.), 139–157. Springer, Cham. https://doi.org/10.1007/978-3-030-58278-4_8
- Barnard L, Portas AM, Gray SL, Harrison RG (2016) The National Eclipse Weather Experiment: An assessment of citizen scientist weather observations. *Philosoph Trans Royal Soc A Math Phys Eng Sci* 374(2077):20150220. <https://doi.org/10.1098/rsta.2015.0220>
- Barnard L, Scott C, Owens M, Lockwood M, Tucker-Hood K, Thomas S, Crothers S, Davies JA, Harrison R, Lintott C, Simpson R, O'Donnell J, Smith AM, Waterson N, Bamford S, Romeo F, Kukula M, Owens B, Savani N, Wilkinson J, Baeten E, Poeffel L, Harder B (2014) The solar Stormwatch CME catalogue: Results from the first space weather citizen science project. *Space Weather* 12(12):657–674. <https://doi.org/10.1002/2014SW001119>
- Bonney R, Ballard H, Jordan R, McCallie E, Phillips T, Shirk J, Wilderman CC (2009a) Public participation in scientific research: Defining the field and assessing its potential for informal science education. A CAISE inquiry group report, Center for Advancement of Informal Science Education (CAISE), Washington, D.C., USA. <https://eric.ed.gov/?id=ED519688>
- Bonney R, Cooper CB, Dickinson J, Kelling S, Phillips T, Rosenberg KV, Shirk J (2009b) Citizen science: A developing tool for expanding science knowledge and scientific literacy. *Bioscience* 59(11):977–984. <https://doi.org/10.1525/bio.2009.59.11.9>
- Bottollier-Depois JF, Allain E, Baumont G, Berthelot N, Darley G, Ecrabet F, Jolivet T, Lebeau-Livé A, Lejeune V, Quéinnec F, Simon C, Trompier F (2019) The Openradiation project: Monitoring radioactivity in the environment by and for the citizens. *Radioprotection* 54(4):241–246. <https://doi.org/10.1051/radiopro/2019046>
- Case NA, Kingman D, MacDonald EA (2016a) A real-time hybrid aurora alert system: Combining citizen science reports with an auroral oval model. *Earth Space Sci* 3(6):257–265. <https://doi.org/10.1002/2016EA000167>
- Case NA, MacDonald EA, Heavner M, Tapia AH, Lalone N (2015) Mapping auroral activity with Twitter. *Geophys Res Lett* 42(10):3668–3676. <https://doi.org/10.1002/2015GL063709>
- Case NA, MacDonald EA, Viereck R (2016b) Using citizen science reports to define the equatorial extent of auroral visibility. *Space Weather* 14(3):198–209. <https://doi.org/10.1002/2015SW001320>
- Chartier AT, Steele J, Sugar G, Themens DR, Vines SK, Huba JD (2023) Validating ionospheric models against technologically relevant metrics. *Space Weather* 21(12):e2023SW003590. <https://doi.org/10.1029/2023SW003590>
- Cohen A, Connor H, Hampton D, Ozturk D, Blandin M, Jung J, Reyes J, Schoening L, Reeve W, Smith C, Keese A (2021) UAF Space Weather UnderGround program: A student-built magnetometer array in Alaska for space science research. In: AGU fall meeting abstracts, vol. 2021, ED15A-0524

- Collins K, Gibbons J, Frissell N, Montare A, Kazdan D, Kalmbach D, Swartz D, Benedict R, Romanek V, Boedicker R, Liles W, Engelke W, McGaw DG, Farmer J, Mikitin G, Hobart J, Kavanagh G, Chakraborty S (2023) Crowdsourced Doppler measurements of time standard stations demonstrating ionospheric variability. *Earth Syst Sci Data* 15(3):1403–1418. <https://doi.org/10.5194/essd-15-1403-2023>
- Collins K, Kazdan D, Frissell NA (2021) Ham radio forms a planet-sized space weather sensor network. *Eos* 102. <https://doi.org/10.1029/2021eo154389>
- Colón Robles M, Amos HM, Dodson JB, Bouwman J, Rogerson T, Bombosch A, Farmer L, Burdick A, Taylor J, Chambers LH (2020) Clouds around the World: How a simple citizen science data challenge became a worldwide success. *Bull Am Meteor Soc* 101(7):E1201–E1213. <https://doi.org/10.1175/BAMS-D-19-0295.1>
- Connor H, Larson S, Gross C, Patino AR, Poh GK, Ozturk D, Owolabi C, Smith C (2024) Maryland space weather underground (SWUG) educational outreach program for solar eclipse study. In: 2024 Triennial earth-sun summit (TESS) meeting
- Cooper CB, Hawn CL, Larson LR, Parrish JK, Bowser G, Cavalier D, Dunn RR, Haklay MM, Gupta KK, Jelks NO, Johnson VA, Katti M, Leggett Z, Wilson OR, Wilson S (2021) Inclusion in citizen science: The conundrum of rebranding. *Science* 372(6549):1386–1388. <https://doi.org/10.1126/science.abi6487>
- Cresswell GR (1969) Flaming auroras. *J Atmos Terr Phys* 31(1):179–183. [https://doi.org/10.1016/0021-9169\(69\)90092-0](https://doi.org/10.1016/0021-9169(69)90092-0)
- Dahlgren H, Aikio A, Kaila K, Ivchenko N, Lanchester BS, Whiter DK, Marklund GT (2010) Simultaneous observations of small multi-scale structures in an auroral arc. *J Atmos Sol Terr Phys* 72:633–637. <https://doi.org/10.1016/j.jastp.2010.01.014>
- Dahlgren H, Lanchester BS, Ivchenko N, Whiter DK (2016) Electrodynamics and energy characteristics of aurora at high resolution by optical methods. *J Geophys Res* 121(6):5966–5974. <https://doi.org/10.1002/2016JA022446>
- Darley G, Berthelot N, Bottollier-Depois J-F, Briand C, Fuller N, L, K, Lejeune V, A, S, Tromprier F (2019) A citizen science project for cosmic radiation monitoring in airplane. <https://doi.org/10.13140/RG.2.2.30077.23527>
- Day D, Bland P, Sayers R (2019) Fireballs in the Sky: Citizen science with the Desert Fireball Network. EPSC Abstracts 13, EPSC-DPS2019-1178-2
- Deacon C, Mitchell C, Watson R, Witvliet BA (2022) Evidence for the magnetoionic nature of oblique VHF reflections from midlatitude sporadic-E layers. *Atmosphere* 13(12):1. <https://doi.org/10.3390/atmos13122027>
- Deacon C, Witvliet B, Mitchell C, Steendam S (2021) Rapid and accurate measurement of polarization and fading of weak VHF signals obliquely reflected from Sporadic-E layers. *IEEE Trans Antennas Propag* 69(7):4033–4048. <https://doi.org/10.1109/TAP.2020.3044654>
- Dora VD (2023) From the radio shack to the cosmos: Listening to Sputnik during the International Geophysical Year (1957–1958). *Isis* 114(1):123–149. <https://doi.org/10.1086/723592>
- Dotzek N, Groenemeijer P, Feuerstein B, Holzer AM (2009) Overview of ESSL's severe convective storms research using the European Severe Weather Database ESWD. *Atmos Res* 93(1):575–586. <https://doi.org/10.1016/j.atmosres.2008.10.020>
- Downs RR, Ramapriyan HK, Peng G, Wei Y (2021) Perspectives on citizen science data quality. *Front Climate* 3:615032. <https://doi.org/10.3389/fclim.2021.615032>
- Dreyer J, Partamies N, Whiter D, Ellingsen PG, Baddeley L, Buchert SC (2021) Characteristics of fragmented aurora-like emissions (FAEs) observed on Svalbard. *Ann Geophys* 39(2):277–288. <https://doi.org/10.5194/angeo-39-277-2021>
- Duquet RT (1959) Meteorology and amateur radio. *Weatherwise* 12(3):104–108. <https://doi.org/10.1080/00431672.1959.10543798>
- Edson LB, MacDonald E, Fischer H, Cawood A (2024) Practical applications of a participatory science project evaluation tool: Perspectives from across Earth and space science. *Citizen Sci Theory Practice* 9(1):10. <https://doi.org/10.5334/cstp.536>
- Eitzel MV, Cappadonna JL, Santos-Lang C, Duerr RE, Virapongse A, West SE, Kyba CCM, Bowser A, Cooper CB, Sforzi A, Metcalfe AN, Harris ES, Thiel M, Haklay M, Ponciano L, Roche J, Ceccaroni L, Shilling FM, Dörler D, Heigl F, Kiessling T, Davis BY, Jiang Q (2017) Citizen science terminology matters: Exploring key terms. *Citizen Sci Theory Practice* 2:1. <https://doi.org/10.5334/cstp.96>
- Fortson L (2021) From green peas to STEVE: Citizen science engagement in space science. In: Bevelacqua J (ed.) *Space science and public engagement: 21st century perspectives and opportunities*, 185–219. <https://doi.org/10.1016/B978-0-12-817390-9.00009-9>

- Frissell NA, Ackermann JR, Alexander JN, Benedict RL, Blackwell WC, Boedicker RK, Cerwin SA, Collins KV, Cowling SH, Deacon C, Diehl DM, Di Mare F, Duffy TJ, Edson LB, Engelke WD, Farmer JO, Frissell RM, Gerzoff RB, Gibbons J, Griffiths G, Holm S, Howell FM, Kaeppler SR, Kavanagh G, Kazdan D, Kim H, Larsen DR, Ledvina VE, Liles W, Lo S, Lombardi MA, MacDonald EA, Madey J, McDermott TC, McGaw DG, McGwier RW, Mikitin GA, Miller ES, Mitchell C, Montare A, Nguyen CD, Nordberg PN, Perry GW, Piccini GN, Pozerski SW, Reif RH, Rizzo JD, Robinett RS, Romanek VI, Sami S, Sanchez DF, Sarwar MS, Schwartz JA, Serra HL, Silver HW, Skov TM, Swartz DA, Themens DR, Tholley FH, West ML, Wilcox RC, Witten D, Witvliet BA, Yadav N (2023) Heliophysics and amateur radio: Citizen science collaborations for atmospheric, ionospheric, and space physics research and operations. *Front Astron Space Sci* 10:1. <https://doi.org/10.3389/fspas.2023.1184171>
- Frissell NA, Katz JD, Gunning SW, Vega JS, Gerrard AJ, Earle GD, Moses ML, West ML, Huba JD, Erickson PJ, Miller ES, Gerzoff RB, Liles W, Silver HW (2018) Modeling amateur radio soundings of the ionospheric response to the 2017 great American eclipse. *Geophys Res Lett* 45(10):4665–4674. <https://doi.org/10.1029/2018GL077324>
- Frissell NA, Miller ES, Kaeppler SR, Ceglia F, Pascoe D, Sinanis N, Smith P, Williams R, Shovkoplyas A (2014) Ionospheric sounding using real-time amateur radio reporting networks. *Space Weather* 12(12):1. <https://doi.org/10.1002/2014SW001132>
- Frissell NA, Moses ML, Earle GD, McGwier R, Silver HW (2015) HamSCI and the 2017 total solar eclipse (HamSCI Founding Document). <https://doi.org/10.5281/zenodo.12666402>
- Frissell NA, Vega JS, Markowitz E, Gerrard AJ, Engelke WD, Erickson PJ, Miller ES, Luetzelshwab RC, Bortnik J (2019) High-frequency communications response to solar activity in September 2017 as observed by amateur radio networks. *Space Weather* 17(1):118–132. <https://doi.org/10.1029/2018SW002008>
- Gadsden M (1998) The North-West Europe data on noctilucent clouds: a survey. *J Atmos Solar Terr Phys* 60(12):1163–1174. [https://doi.org/10.1016/S1364-6826\(98\)00072-8](https://doi.org/10.1016/S1364-6826(98)00072-8)
- Gallardo-Lacourt B, Nishimura Y, Kepko L, Spanswick EL, Gillies DM, Knudsen DJ, Burchill JK, Skone SH, Pinto VA, Chaddock D, Kuzub J, Donovan EF (2024) Unexpected STEVE observations at high latitude during quiet geomagnetic conditions. *Geophys Res Lett* 51(19):e2024GL110568. <https://doi.org/10.1029/2024GL110568>
- Gibbons J, Collins K, Kazdan D, Frissell N (2022) Grape version 1: First prototype of the low-cost personal space weather station receiver. *HardwareX* 11:e00289. <https://doi.org/10.1016/J.OHX.2022.E00289>
- Gjerloev JW, Barnes R, Eisape A, Mosavi-Hoyer N, Cline T, Kalapala C, Seelman P, Rathbun H (2024) EZIE-Mag: Empowering students nationwide in space science exploration and education. In: Small satellite conference proceedings. <https://digitalcommons.usu.edu/smallsat/2024/all2024/27/> Accessed 17 April 2025
- Gonzalez-Esparza JA, Sanchez-Garcia E, Sergeeva M, Corona-Romero P, Gonzalez-Mendez LX, Valdes-Galicia JF, Aguilar-Rodriguez E, Rodriguez-Martinez M, Ramirez-Pacheco C, Castellanos CI, Pazos M, Mendoza B, Gatica-Acevedo VJ, Melgarejo-Morales A, Caraballo R, Andrade-Mascote E, Villanueva-Hernandez P, Bonifaz-Alfonzo R, Sierra P, Romero-Hernandez E, Peralta-Mendoza I, Perez-Tijerina E, Mejia-Ambriz JC, Guerrero-Peña C, Caccavari A, Cifuentes-Nava G, Hernandez-Quintero E (2024) The Mother's Day geomagnetic storm on 10 May 2024: Aurora observations and low latitude space weather effects in Mexico. *Space Weather* 22(11):e2024SW004111. <https://doi.org/10.1029/2024SW004111>
- Grandin M, ARCTICS collaboration (2024): Citizen science reports on aurora sighting and technological disruptions during the 10 May 2024 geomagnetic storm - ARCTICS survey [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.12732615>
- Grandin M, Bruus E, Ledvina VE, Partamies N, Barthelémy M, Martinis C, Dayton-Oxland R, Gallardo-Lacourt B, Nishimura Y, Herlingshaw K, Thomas N, Karvinen E, Lach D, Spijkers M, Bergstrand C (2024) The Gannon Storm: Citizen science observations during the geomagnetic superstorm of 10 May 2024. *Geosci Commun* 7(4):297–316. <https://doi.org/10.5194/gc-7-297-2024>
- Grandin M, Palmroth M, Whipples G, Kallikokoski M, Ferrier M, Paxton LJ, Mlynarczyk MG, Hilska J, Holmseth K, Vinorum K, Whenman B (2021) Large-scale dune aurora event investigation combining citizen scientists' photographs and spacecraft observations. *AGU Adv* 2(2):e2020AV000338. <https://doi.org/10.1029/2020AV000338>
- Halley E (1715) III. Observations of the late total eclipse of the sun on the 22d of April last past, made before the Royal Society at their house in Crane Court in Fleet-street, London. By Dr. Edmund Halley, Reg. Soc. Secr. With an account of what has been communicated from aboard concerning the same. *Philosoph Trans Royal Soc London* 29(343), 245–262 <https://doi.org/10.1098/rstl.1714.0025>
- Hartstone-Rose, A., Mulvey, K.L., Paciulli, L., Absher, R., Atkinson, N., Wilson, B., Hunter, D.L., Severino, M., Cooper, C.: Extraordinary darkness: A participatory approach to assessing animal

- behavior during eclipses. In: *Bulletin of the American Astronomical Society*, vol. 56, 2024–3003 (2024). <https://doi.org/10.3847/25c2feb.75395fbc>
- Hayakawa H, Ebihara Y, Mishev A, Koldobskiy S, Kusano K, Bechet S, Yashiro S, Iwai K, Shinbori A, Mursula K, Miyake F, Shiota D, Silveira MVD, Stuart R, Oliveira DM, Akiyama S, Ohnishi K, Ledvina V, Miyoshi Y (2025) The solar and geomagnetic storms in 2024 May: A flash data report. *Astrophys J* 979(1):49. <https://doi.org/10.3847/1538-4357/ad9335>
- Heino, E, Partamies, N: Observational validation of cutoff models as boundaries of solar proton event impact area. *J Geophys Res (Space Physics)* 125(7): e2020JA027935 (2020) <https://doi.org/10.1029/2020JA027935>
- Herlingshaw K, Lach D, Dayton-Oxland R, Bruus E, Karvinen E, Ledvina V, Partamies N, Grandin M, Spijkers M, Nishimura Y, Knudsen D, Ladbroke L, Martinis C, Gallardo-Lacourt B, Dyer A, Mielke L, Ratzlaff C, Evans L, Helin M, Kuzub J, Barthelemy M, Thomas N, Glad M, Donovan E, Syrjäso M, Cordon S, Andersen J, Legg C (2024) ARCTICS aurora field guide and handbook for citizen science. Zenodo. <https://doi.org/10.5281/zenodo.13931939>
- Hudson H, Petricolas L, Johnson C, White V, Bender M, Pasachoff JM, Oliveros JCM, Filippenko AV et al (2021) The eclipse megamovie project (2017). *J Astronom History Heritage* 24(4):1080–1089. <https://doi.org/10.3724/SP.J.1440-2807.2021.04.17>
- Hunnekuhl M, MacDonald E (2020) Early ground-based work by auroral pioneer Carl Størmer on the high-altitude detached subauroral arcs now known as “STEVE”. *Space Weather* 18(3):e2019SW002384. <https://doi.org/10.1029/2019SW002384>
- Karttunen H (2021) *Ursan Historia: Tähtitieteellinen Yhdistys Ursaa 1921–2021. Tähtitieteellinen Yhdistys Ursaa Ry*, Helsinki, Finland
- Kataoka R, Reddy SA, Nakano S, Pettit J, Nakamura Y (2024) Extended magenta aurora as revealed by citizen science. *Sci Rep* 14(1):25849. <https://doi.org/10.1038/s41598-024-75184-9>
- King-Hele D (2005) *A Tapestry of Orbits*. Cambridge University Press, Cambridge, United Kingdom. <https://doi.org/10.1017/CBO9780511564222>
- Kogogin DA, Nasyrov IA, Maksimov DS, Zagretinov RV (2021) Using Android smartphones with dual-frequency multi-GNSS receiver to measure the total electron content of the ionosphere. *J Phys: Conf Ser* 1991(1):012025. <https://doi.org/10.1088/1742-6596/1991/1/012025>
- Können GP, Hinz C (2008) Visibility of stars, halos, and rainbows during solar eclipses. *Appl Opt* 47(34):H14–H24. <https://doi.org/10.1364/AO.47.000H14>
- Kosar BC, MacDonald EA, Case NA, Zhang Y, Mitchell EJ, Viereck R (2018) A case study comparing citizen science aurora data with global auroral boundaries derived from satellite imagery and empirical models. *J Atmos Solar Terr Phys* 177:274–282. <https://doi.org/10.1016/j.jastp.2018.05.006>
- Kosmala M, Wiggins A, Swanson A, Simmons B (2016) Assessing data quality in citizen science. *Front Ecol Environ* 14(10):551–560. <https://doi.org/10.1002/fee.1436>
- Krukowski S, Amarasinghe I, Gutiérrez-Páez NF, Hoppe HU (2022) Does volunteer engagement pay off? An analysis of user participation in online citizen science projects. In: Wong L-H, Hayashi Y, Collazos CA, Alvarez C, Zurita G, Baloian N (eds.) *Collaboration technologies and social computing*, 67–82. Springer, Cham. https://doi.org/10.1007/978-3-031-20218-6_5
- Kuzub J (2022) AurorEye: Production of a portable, Off-the-shelf automated all-sky aurora camera. In: *AGU fall meeting abstracts*, vol. 2022, SH51D-04
- Kyba CCM, Altıntaş YÖ, Walker CE, Newhouse M (2023) Citizen scientists report global rapid reductions in the visibility of stars from 2011 to 2022. *Science* 379(6629):265–268. <https://doi.org/10.1126/science.abq7781>
- Larson LR, Conway AL, Hernandez SM, Carroll JP (2016) Human-wildlife conflict, conservation attitudes, and a potential role for citizen science in Sierra Leone, Africa. *Conserv Soc* 14(3):205–217. <https://doi.org/10.4103/0972-4923.191159>
- Ledvina V, Brandt L, MacDonald E, Frissell N, Anderson J, Chen TY, French RJ, Di Mare F, Grover A, Battams K, Sigsbee K, Gallardo-Lacourt B, Lach D, Shaw JA, Hunnekuhl M, Kosar B, Barkhouse W, Young T, Kedhambadi C, Ozturk DS, Claudepierre SG, Dong C, Witteman A, Kuzub J, Sinha G (2023) Agile collaboration: Citizen science as a transdisciplinary approach to heliophysics. *Front Astron Space Sci* 10. <https://doi.org/10.3389/fspas.2023.1165254>
- Lo S, Rankov N, Mitchell C, Witvliet BA, Jayawardena TP, Bust G, Liles W, Griffiths G (2022) A systematic study of 7 MHz greyline propagation using amateur radio beacon signals. *Atmosphere* 13(8). <https://doi.org/10.3390/atmos13081340>
- Lotfian M, Ingensand J, Brovelli MA (2020) A framework for classifying participant motivation that considers the typology of citizen science projects. *ISPRS Int J Geo-Inform* 9(12). <https://doi.org/10.3390/ijgi9120704>

- MacDonald EA, Case NA, Clayton JH, Hall MK, Heavner M, Lalone N, Patel KG, Tapia A (2015) Auro-rasaurus: A citizen science platform for viewing and reporting the aurora. *Space Weather* 13(9):548–559. <https://doi.org/10.1002/2015SW001214>
- MacDonald EA, Donovan E, Nishimura Y, Case NA, Gillies DM, Gallardo-Lacourt B, Archer WE, Spans-wick EL, Bourassa N, Connors M, Heavner M, Jackel B, Kosar B, Knudsen DJ, Ratzlaff C, Schofield I (2018) New science in plain sight: Citizen scientists lead to the discovery of optical structure in the upper atmosphere. *Sci Adv* 4(3):eaq0030. <https://doi.org/10.1126/sciadv.aq0030>
- Marshall PJ, Lintott CJ, Fletcher LN (2015) Ideas for citizen science in astronomy. *Ann Rev Astron Astro-phys* 53:247–278. <https://doi.org/10.1146/annurev-astro-081913-035959>
- Martinis C, Griffin I, Gallardo-Lacourt B, Wroten J, Nishimura Y, Baumgardner J, Knudsen DJ (2022) Rainbow of the night: First direct observation of a SAR arc evolving into STEVE. *Geophys Res Lett* 49(11):e2022GL098511. <https://doi.org/10.1029/2022GL098511>
- McCray WP (2006) Amateur scientists, the International Geophysical Year, and the ambitions of Fred Whipple. *Isis* 97(4):634–658. <https://doi.org/10.1086/509947>
- Moilanen J, Gritsevich M (2022) Light scattering by airborne ice crystals - An inventory of atmospheric halos. *J Quant Spectros Radiative Transf* 290. <https://doi.org/10.1016/j.jqsrt.2022.10831>
- Musset S, Jol P, Sankar R, Alnahari S, Kapsiak C, Ostlund E, Lasko K, Glesener L, Fortson L, Fleish-man GD, Panesar NK, Zhang Y, Jeunon M, Hurlburt N (2024) Solar Jet Hunter: A citizen science initiative to identify and characterize coronal jets at 304 Å. *Astron Astrophys* 688:A127. <https://doi.org/10.1051/0004-6361/202348074>
- Nanjo S, Hofstra GA, Shiokawa K, Shinbori A, Nozawa S, Hosokawa K (2024) Post-midnight purple arc and patches appeared on the high latitude part of the auroral oval: Dawnside counterpart of STEVE? *Earth Planets Space* 76(1):55. <https://doi.org/10.1186/s40623-024-01995-9>
- Nanjo S, Nozawa S, Yamamoto M, Kawabata T, Johnsen MG, Tsuda TT, Hosokawa K (2022) An auto-mated auroral detection system using deep learning: Real-time operation in Tromsø, Norway. *Sci-entif Rep* 12:8038. <https://doi.org/10.1038/s41598-022-11686-8>
- Nanjo S, Shiokawa K (2024) Spatial structures of blue low-latitude aurora observed from Japan during the extreme geomagnetic storm of May 2024. *Earth Planets Space* 76(1):156. <https://doi.org/10.1186/s40623-024-02090-9>
- Nevanlinna H (2009) FMI Reports, Revontulihavainnot Suomessa 1748-2009. <http://hdl.handle.net/10138/14079> Accessed 17 April 2025
- Nevanlinna H, Bruus E, Brandström U (2024) 1950-1970 Aurora observation samples from Finland and Sweden in Skywarden. <https://www.taivaanvahti.fi/app/api/search.php?language=en&start=1950-01-01&end=1970-01-01&columns=all&category=2&columns=all&format=html> Accessed 17 April 2025
- Nishimura Y, Bruus E, Karvinen E, Martinis CR, Dyer A, Kangas L, Rikala HK, Donovan EF, Nishitani N, Ruohoniemi JM (2022) Interaction between proton aurora and stable auroral red arcs unveiled by citizen scientist photographs. *J Geophys Res Space Phys* 127(7):e2022JA030570. <https://doi.org/10.1029/2022JA030570>
- Oh RRY, Suarez-Castro AF, Fuller RA, Tervo M, Rozario K, Peters B, Chowdhury S, Gönner J, Frie-drichs-Manthey M, Berger A, Schultz T, Dean AJ, Tulloch A, Bonn A (2025) Using nature-based citizen science initiatives to enhance nature connection and mental health. *Front Environ Sci* 13. <https://doi.org/10.3389/fenvs.2025.1461601>
- Ozturk DS, Cohen A, Barkley-Griggs J, Schoening L, Hampton DL, Reeve WD, Connor H, Smith CW, Keese AM (2023) Advancing space weather research in Alaska through collaborations with high schools: The Space Weather UnderGround program. In: AGU fall meeting abstracts, vol. 2023, ED11A-04
- Palmroth M, Grandin M, Helin M, Koski P, Oksanen A, Glad MA, Valonen R, Saari K, Bruus E, Nor-berg J, Viljanen A, Kauristie K, Verronen PT (2020) Citizen scientists discover a new auroral form: Dunes provide insight into the upper atmosphere. *AGU Adv* 1(1):e2019AV000133. <https://doi.org/10.1029/2019AV000133>
- Parviainen P, Bohren CF, Mäkelä V (1994) Vertical elliptical coronas caused by pollen. *Appl Opt* 33:4548–4551. <https://doi.org/10.1364/AO.33.004548>
- Patterson JD, Armstrong TP, Laird CM, Detrick DL, Weatherwax AT (2001) Correlation of solar ener-getic protons and polar cap absorption. *J Geophys Res* 106(A1):149–164. <https://doi.org/10.1029/2000JA002006>
- Pekkola M (1991) Finnish halo observing network: Search for rare halo phenomena. *Appl Opt* 30:3542–3544. <https://doi.org/10.1364/AO.30.003542>

- Perry GWW, Frissell NAA, Miller ESS, Moses M, Shovkoplyas A, Howarth ADD, Yau AWW (2018) Citizen radio science: An analysis of amateur radio transmissions with e-POP RRI. *Radio Sci* 53:933–947. <https://doi.org/10.1029/2017RS006496>
- Portas AM, Barnard L, Scott C, Harrison RG (2016) The National Eclipse Weather Experiment: Use and evaluation of a citizen science tool for schools outreach. *Philosoph Trans Royal Soc A Math Phys Eng Sci* 374(2077):20150223. <https://doi.org/10.1098/rsta.2015.0223>
- Purtova N, Pierce RL (2024) Citizen scientists as data controllers: Data protection and ethics challenges of distributed science. *Comput Law Security Rev* 52:105911. <https://doi.org/10.1016/j.clsr.2023.105911>
- Ramapriyan H, Peng G, Moroni D, , Shie C-L (2017) Ensuring and improving information quality for Earth science data and products. *D-Lib Magaz* 23. <https://doi.org/10.1045/july2017-ramapriyan>
- Rappaport TS (2022) Crucible of communications: How amateur radio launched the information age and brought high tech to life: Part 1: The birth and breadth of the ham radio hobby (invited article). *IEEE Commun Mag* 60(10):6–10. <https://doi.org/10.1109/MCOM.2022.9928087>
- Rappaport TS (2023) Crucible of communications: How amateur radio launched the information age and brought high tech to life part 2: Hams bring real-time communications to the world (invited article). *IEEE Commun Mag* 61(11):10–23. <https://doi.org/10.1109/MCOM.2023.10328195>
- Riesch H, Potter C (2014) Citizen science as seen by scientists: Methodological, epistemological and ethical dimensions. *Public Underst Sci* 23(1):107–120. <https://doi.org/10.1177/0963662513497324>
- Riikonen M, Ruuskanen J (1994) Observations of vertically elliptical halos. *Appl Opt* 33(21):4537–4538. <https://doi.org/10.1364/AO.33.004537>
- Rogers AEE, Lekberg M, Pratap P (2009) Seasonal and diurnal variations of ozone near the mesopause from observations of the 11.072-GHz Line. *J Atmos Oceanic Tech* 26(10):2192. <https://doi.org/10.1175/2009JTECHA1291.1>
- Schröder W (2007) Amateur observations of atmospheric phenomena during the IGY. *EOS Trans Am Geophys Union* 88(12):141–143. <https://doi.org/10.1029/2007EO120002>
- Seaton DB, Caspi A, Alzate N, Davis SJ, DeForest AR, DeForest CE, Erickson NF, Kovac SA, Patel R, Osterman SN, Tosolini A, Van Kooten SJ, West MJ (2024) Observations of the polarized solar corona during the annular eclipse of 14 October 2023. *Sol Phys* 299(6):79. <https://doi.org/10.1007/s11207-024-02297-9>
- Semeter J, Hunnekuhl M, MacDonald E, Hirsch M, Zeller N, Chernenkoff A, Wang J (2020) The mysterious green streaks below STEVE. *AGU Adv* 1(4):e2020AV000183. <https://doi.org/10.1029/2020A0000183>
- Severino M, Perrett K, Giles E, Arbuckle D, Emslie AG, Hudson HS, Nickerson C, Moundalak R, Arbuckle G, Galloway J, Cavalier D (2025) A model for success: How SciStarter's partnerships with eclipse soundscapes and SunSketcher engaged communities and amplified impact in participatory science. *Bull Am Astron Soc* 56:2024–9028. <https://doi.org/10.3847/25c2cf.5792d55f>
- Shirk JL, Ballard HL, Wilderman CC, Phillips T, Wiggins A, Jordan R, McCallie E, Minarchek M, Lewenstein BV, Krasny ME et al (2012) Public participation in scientific research: A framework for deliberate design. *Ecol Soc* 17(2). <https://doi.org/10.5751/ES-04705-170229>
- Sillanpää M, Moilanen J, Pekkola M, Penttinen M, Piikki J (1999) Unusual pyramidal ice in the atmosphere as the origin of elliptical halos. *Appl Opt* 38(24):5089–5095. <https://doi.org/10.1364/AO.38.005089>
- Smith CW, Blackwell JA, Ercoline L, Goelzer S, Kucharek H, Lessard M, Levergood R, Reeve WD, Routhier MR, Schwadron N, Watson A, Young C, Johnson A (2019) The Space Weather Underground: A student-built array of ground-based fluxgate magnetometers in Northern New England. In: *AGU Fall Meeting Abstracts*, vol. 2019, ED23A-04
- Snik F, Rietjens JHH, Apituley A, Volten H, Mijling B, Di Noia A, Heikamp S, Heinsbroek RC, Hasekamp OP, Smit JM, Vonk J, Stam DM, Harten G, Boer J, Keller CU (2014) Mapping atmospheric aerosols with a citizen science network of smartphone spectropolarimeters. *Geophys Res Lett* 41(20):7351–7358. <https://doi.org/10.1002/2014GL061462>
- Soja A (2022) Thoughts about the outreach project “Science on the Frontier: Expanding the Limits of Knowledge”. In: Schultz, G., Jensen, J.B., Shore, L. (eds.) *ASP 2021: Sharing best practices - astronomyteaching and public engagement*. In: *Astronomical society of the pacific conference series*, vol. 533, 151
- Southworth MP (1960) Night-time equatorial propagation at 50 Mc/s: First results from an IGY amateur observing program. *J Geophys Res* (1896-1977) 65(2):601–607. <https://doi.org/10.1029/JZ065i002p00601>
- Southworth MP (1959) A look back and ahead at PRP. *QST* 43:48–49

- Spasiano A, Grimaldi S, Braccini AM, Nardi F (2021) Towards a transdisciplinary theoretical framework of citizen science: Results from a meta-review analysis. *Sustainability* 13(14):7904. <https://doi.org/10.3390/su13147904>
- Spogli L, Alberti T, Bagiacchi P, Cafarella L, Cesaroni C, Cianchini G, Coco I, Di Mauro D, Ghidoni R, Giannattasio F, Ippolito A, Marocci C, Pezzopane M, Pica E, Pignalberi A, Perrone L, Romano V, Sabbagh D, Scotto C, Spadoni S, Tozzi R, Viola M (2024) The effects of the May 2024 Mother's Day superstorm over the Mediterranean sector: From data to public communication. *Ann Geophys* 67(2):PA218. <https://doi.org/10.4401/ag-9117>
- Stauning P (2011) Danish auroral science history. *History Geo- Space Sci* 2(1):1–28. <https://doi.org/10.5194/hgss-2-1-2011>
- Stoffregen W (1955) All-sky camera auroral research during the Third Geophysical Year 1957–58. *Tellus* 7(4):509–517. <https://doi.org/10.1111/j.2153-3490.1955.tb01188.x>
- Taylor J, Walker B (2010) WSPRring around the world. *QST* 94:30–32
- Tolbert S, Olson C, Haq RU, Evans L, Santos APO, Franco AA, Jager I, Kovač M, Orchard S, Harris S et al (2024) 'Citizen Scientists' on citizen science. *Postdigital Sci Edu* 7:120–142. <https://doi.org/10.1007/s42438-024-00494-0>
- Tomaščík J, Varga M, Everett T (2024) Raw GNSS data collected using smartphones and low-cost receiver under optimal and sub-optimal conditions. *Data Brief* 53:110148. <https://doi.org/10.1016/j.dib.2024.110148>
- van den IJssel J, Doornbos E, Iorfida E, March G, Siemes C, Montenbruck O (2020) Thermosphere densities derived from Swarm GPS observations. *Adv Space Res* 65(7):1758–1771. <https://doi.org/10.1016/j.asr.2020.01.004>
- Vohland K, Weißpflug M, Pettibone L (2019) Citizen science and the neoliberal transformation of science - an ambivalent relationship. *Citizen Sci Theory Practice* 4:25. <https://doi.org/10.5334/cstp.186>
- Walden MC (2012) Comparison of propagation predictions and measurements for midlatitude HF near-vertical incidence sky wave links at 5 MHz. *Radio Sci* 47(4). <https://doi.org/10.1029/2011RS004914>
- Walden MC (2016) High-frequency near vertical incidence skywave propagation: Findings associated with the 5 MHz experiment. *IEEE Antennas Propag Mag* 58(6):16–28. <https://doi.org/10.1109/MAP.2016.2609798>
- Walmsley M, Smith L, Lintott C, Gal Y, Bamford S, Dickinson H, Fortson L, Kruk S, Masters K, Scarlata C, Simmons B, Smethurst R, Wright D (2020) Galaxy Zoo: probabilistic morphology through Bayesian CNNs and active learning. *Mon Not R Astron Soc* 491(2):1554–1574. <https://doi.org/10.1093/mnras/stz2816>
- Whiter DK, Sundberg H, Lanchester BS, Dreyer J, Partamies N, Ivchenko N, Di Fraia MZ, Oliver R, Serpell-Stevens A, Shaw-Diaz T, Brauersreuther T (2021) Fine-scale dynamics of fragmented auroral-like emissions. *Ann Geophys* 39(6):975–989. <https://doi.org/10.5194/angeo-39-975-2021>
- Wilkinson MD, Dumontier M, Aalbersberg IJ, Appleton G, Axton M, Baak A, Blomberg N, Boiten J-W, Silva Santos LB, Bourne PE et al (2016) The FAIR guiding principles for scientific data management and stewardship. *Scientific data* 3(1):1–9. <https://doi.org/10.1038/sdata.2016.18>
- Williams B, Geraschenko A, Kast A, Smith J, Morton J (2023) Using phones to map the ionosphere total electron content and improve location accuracy. In: AGU fall meeting abstracts, vol. 2023, G54A-02
- Witvliet BA, Alsina-Pagès RM (2017) Radio communication via near vertical incidence Skywave propagation: An overview. *Telecommun Syst* 66:295–309. <https://doi.org/10.1007/s11235-017-0287-2>
- Witvliet BA, Maanen EV, Petersen GJ, Westenberg AJ, Bentum MJ, Slump CH, Schiphorst R (2015) Near vertical incidence skywave propagation: Elevation angles and optimum antenna height for horizontal dipole antennas. *IEEE Antennas Propag Mag* 57:129–146. <https://doi.org/10.1109/MAP.2015.2397071>
- Witvliet BA, Maanen E, Petersen GJ, Westenberg AJ (2016) Impact of a solar X-flare on NVIS propagation: Daytime characteristic wave refraction and nighttime scattering. *IEEE Antennas Propag Mag* 58(6):29–37. <https://doi.org/10.1109/MAP.2016.2609678>
- Wright DE, Fortson L, Lintott C, Laraia M, Walmsley M (2019) Help me to help you: Machine augmented citizen science. *Trans. Soc. Comput.* 2(3):11–11120. <https://doi.org/10.1145/3362741>
- WsprDaemon group (2024) Response to: The FCC's PSHSB seeks comment on the impacts of the May 2024 geomagnetic storm on the U.S. communications sector. https://hamsci.org/sites/default/files/WsprDaemon_Comments_FCC_24-161_redacted.pdf Accessed 17 April 2025
- Yeang C-P (2013) Probing the sky with radio waves: From wireless technology to the development of atmospheric science. University of Chicago Press, Chicago, IL, USA. <https://doi.org/10.7208/chicago/9780226034812.001.0001>
- Young T, Ledvina V, MacDonald E, Brandt L, McCormack M, Collins S, Barkhouse W (2022) The North Dakota Dual Aurora Camera version 2.0 (NoDDAC2.0), a Platform for citizen science and a testbed

for implementing best practices in open data and collaboration. In: AGU fall meeting abstracts, vol. 2022, SH52F-1512

Zevin M, Jackson CB, Doctor Z, Wu Y, Østerlund C, Johnson LC, Berry CPL, Crowston K, Coughlin SB, Kalogera V, Banagiri S, Davis D, Glanzer J, Hao R, Katsaggelos AK, Patane O, Sanchez J, Smith J, Soni S, Trouille L, Walker M, Aerith I, Domainko W, Baranowski V-G, Niklasch G, Téglás B (2024) Gravity Spy: Lessons learned and a path forward. *Eur Phys J Plus* 139(1):100. <https://doi.org/10.1140/epjp/s13360-023-04795-4>

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