

Aurorasaurus: a Citizen Science Platform for Viewing and Reporting the Aurora

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Abstract. A new, citizen science based, aurora observing and reporting platform has been developed with the primary aim of collecting auroral observations made by the general public to further improve the modeling of the aurora. In addition, the real-time ability of this platform facilitates the combination of citizen science observations with auroral oval models to improve auroral visibility nowcasting. Aurorasaurus provides easily understandable aurora information, basic gamification, and real-time location-based notification of verified aurora activity to engage citizen scientists. The Aurorasaurus project is one of only a handful of space weather citizen science projects and can provide useful results for the space weather and citizen science communities. Early results are promising with over 2,000 registered users submitting over 1,000 aurora observations and verifying over 1,700 aurora sightings posted on Twitter.

1. Introduction

Citizen science is a rapidly growing, newly formalized, field that is fueled by the concept of crowdsourcing and cognitive surplus, i.e. that small amounts of volunteered time from a vast number of people can contribute to a larger goal [Shirky, 2010]. Specifically, citizen science involves “organized research in which members of the public engage in the processes of scientific investigations by asking questions, collecting data, and/or interpreting results” (Citizen Science Central, <http://www.citizenscience.org>).

Projects that incorporate citizen science have the potential to engage broad audiences, motivate volunteers, increase data collection yet still control data quality, corroborate model results, and increase the speed at which decisions can be made [Clery, 2011; Cooper et al., 2010; Danielsen et al., 2010; Darg et al., 2011; Kelling et al., 2009; Willett et al., 2010].

Such projects are frequent and well established in astronomy, fueled by the large and well organized amateur astronomy networks (e.g. Globe at Night [Walker et al., 2008], Zooniverse [Smith et al., 2013] and Cosmoquest [Gugliucci et al., 2014]). Similarly, in biological fields, citizen science programs are widespread and tend to be based upon the crowd-sourced collection of phenological or conservation-related data [Wiggins and Crowston, 2010]. However, formal citizen science projects are fairly rare in the field of solar-terrestrial physics [Knipp, 2015]. One specific example is Barnard et al. [2014] who, in partnership with the leading citizen science astronomy collective Zooniverse, have created a data analysis citizen science project involving the characterization of coronal mass ejections. There are, however, many informal groups or individuals who are functioning

as citizen scientists, e.g. ham radio operators (c.f. *Coile* [1997]), sprite hunters (c.f. *Lyons et al.* [2012]), and northern lights hunters (e.g. *Frissell et al.* [2014]).

An early, well known, aurora hunting citizen scientist was a Vermont farmer named Wilson Bentley who observed and cataloged over 700 auroras over a century ago [*Silverman and Blanchard*, 1983]. Today, there are many aurora hunting citizen scientists like Bentley, partly enabled by the advent of easy-to-use and sensitive digital photography. This advancement in photographic equipment allows even subvisual aurora to be captured and observed on the camera, typically after an exposure of a minute or less.

With the arrival of new technological tools, such as smartphones and social networks, public participation in scientific practice has been enabled and supported as never before. Citizen science can work on a massive scale, generating high quality data that lead to reliable, valid scientific outcomes, as well as unexpected insights and innovations [*Fore et al.*, 2001; *Trumbull et al.*, 2000].

Exploiting these new technological tools and advancements, Aurorasaurus is a citizen science project whose primary aim is to combine traditional space weather data, i.e. satellite data, with citizen science data, i.e. aurora sightings provided by the public, to improve both our understanding of the aurora and our ability to predict when, and from where, it might be visible.

A more detailed summary of what Aurorasaurus is, along with the data it collects and its outputs, is provided in section 2. A discussion of the relevance of Aurorasaurus to the solar-terrestrial community is presented in section 3 and some early results are shown in section 4. A conclusion, given in section 5, provides a summary of Aurorasaurus and explores potential future developments of the project.

2. What is Aurorasaurus?

Aurorasaurus is an interdisciplinary effort encompassing space weather science, citizen science, and information sciences. The core aspect of the project is to collect citizen science observations of the aurora and use these to improve the real-time nowcasting of its visibility. However, the project also has the broad goals of developing a real-time citizen science network, educating the general public about the aurora and space weather in general, and providing a test-bed for citizen-science based alert systems.

As shown in Figure 1, inputs into the Aurorasaurus platform include data from satellites, citizen scientists and Twitter. These data are processed and displayed on a map, as they relate to the location of the aurora. The process by which raw data are transformed into actionable outcomes and educational activities is also described.

Since the primary function of Aurorasaurus is to let users know when, and from where, an aurora may be visible, the landing page of the website is a real-time aurora map. However, visitors to the site are also able to change the view to select times and dates from the past - thus allowing them to inspect specific events of interest. As shown in Figure 2, overlaid on this are several layers, each of which can be turned on or off by the visitor. These layers include the estimated current and forecasted auroral ovals (based upon the *Roble and Ridley* [1987] model) along with “geosocial” observations, current weather conditions and cloud cover, and a day/night line.

The relatively new term “geosocial” refers to the mapping of socially crowd-sourced observations. Several other platforms that utilize geosocial mapping at their core include: Waze, for real-time traffic and routing information (www.waze.com); eBird, for observations of birds [*Sullivan et al.*, 2009; *Wood et al.*, 2011]; and CoCoRaHS, for weather

observations [Reges *et al.*, 2008]. All of these examples have some similarity in form and function to Aurorasaurus though on vastly different topics and using different types of geosocial data.

2.1. Data Collection

Aurorasaurus collects two forms of geosocial data: aurora observations that are reported directly through either the project's website or mobile apps, and aurora observations that are posted on Twitter.

Both registered and anonymous users may reports observations through the website or mobile apps. These observations are submitted through a template submission form and will often include details about the aurora alongside the required location and time of the sighting. There is also the facility to upload a photograph of the observed aurora . An example of such an observation is shown in Figure 3, along with the form users submit their observations with. The submission form is designed for simplicity by splitting an observation into several key components, including the colors observed, the activity level (in terms of speed), the height in the sky (in terms of the angle from the horizon) and some very basic typology options for the auroral shape. Users report their observations using the simple aurora classifications of discrete arcs, diffuse glow and pulsating patches as these are the most easily distinguishable types of aurora and correspond to different physical mechanisms. An additional comments field allow users to add any extra details not covered by the previous fields.

Whilst the citizen science observations are extremely useful, they can be somewhat limited in availability. The primary issue is that it requires aurora observers to know of the project before their sighting occurs. Therefore, to complement these data, and to

increase the number of observations, Aurorasaurus searches Twitter for any sightings that might have been posted there.

Twitter has been used as a reliable source of information for many large scale events and natural disasters. For example, Twitter users, who post short updates (140 characters max.) known as “tweets”, have provided real-time publicly-available information about events such as earthquakes [Earle *et al.*, 2010; Crooks *et al.*, 2013], influenza outbreaks [Culotta, 2010; Lampos *et al.*, 2010], wildfires [Sutton *et al.*, 2008] and service outages [Motoyama *et al.*, 2010]. Typically such events produce a significant localized rise and exponential decay pattern in the number of tweets relating to that event [Sakaki *et al.*, 2010].

Previous studies have shown that during natural disasters, such as fires and floods, Twitter can be used to evaluate the situation on the ground in real-time (a process known as “crowdcrafting”) (e.g. Vieweg *et al.* [2010]). It therefore seemed plausible that Twitter could be used in a similar way to map the visibility of the aurora.

During a “proof of concept” event in late October 2011, Priedhorsky *et al.* [2012] found that social media networks can be used to detect widespread visible aurora. Case *et al.* [2015a], using data collected by the prototype Aurorasaurus website, expanded this result and showed that, over a period of eight months, the number of tweets correlated well with several proxies of auroral activity (i.e. Kp, Dst, AE and ϵ).

Aurorasaurus uses the Twitter Search API to identify tweets containing any of several aurora-related keywords (e.g. “aurora”, “northern lights”). Some filtering is undertaken on the tweets (for example to remove tweets containing profanity) and an attempt at location extraction is made on the tweets. Some tweets contain location

information embedded within them (i.e. the user has opted to share their GPS location). For those that do not, we use the open-source CLAVIN geo-parser software (<http://clavin.bericotechnologies.com/>) to extract a location based upon the text in the tweet. Such extraction methods can never be perfect, however CLAVIN has shown to have a high precision rate [D'Ignazio et al., 2014].

A best practice of using people to validate the text of tweets has developed (e.g. Yu et al. [2012]) as filtering alone, even when exploiting machine learning, can never be perfect. For example, it is especially difficult for a machine to discern a recent viewing of aurora (e.g. "I've just seen the aurora!") from a desire to see aurora (e.g. "I just want to see the aurora!"). As such, Aurorasaurus serves pre-filtered aurora-related tweets to its users for verification (examples are shown in Figure 4). Our users are encouraged to vote on whether the tweets are genuine real-time sightings of the aurora or not. If enough users vote that a tweet is real sighting, the tweet is "verified" and is treated just like an observation reported by a citizen scientist on the website or through the mobile app. By combining the verified tweets with the reported observations we are able to enrich our dataset and provide greater spatial coverage [Tapia et al., 2011].

So far, the number of verified tweets represents only ~3% of the total number of aurora-related tweets collected. However, preliminary findings suggest that the tweets are a significant source of aurora sightings and can rival or surpass the number of citizen science observations submitted directly to the project. Future work will investigate the efficacy of the citizen science tweet validation and explore more advanced filtering methods.

2.2. Aurora Alerts

Aurorasaurus offers real-time alerts, sent via email and Twitter direct messages, to its registered users when an aurora might be visible near them. To do this, we employ a clustering algorithm on the citizen scientist data (both reported observations and verified tweets). If a certain number of positive sightings are reported in a localized area, which we term a positive cluster, any users located inside that cluster are informed that the aurora has been seen nearby. Users outside, but still nearby, the cluster are informed that an aurora may be visible near them.

In the current implementation, alerts are issued solely based on the citizen science data. Future iterations of the project, which are currently under development, will merge the output from the auroral oval models and the positive sighting clusters to provide a more robust real-time alert system. Specifically, the auroral ovals will adapt to any positive sighting clusters thus providing a responsive, high resolution estimate of where the aurora can be seen. In turn, this will feed in to more accurate alerts for our users.

This hybrid alert system will be more precise than the coarse, large-scale, alerts based on the solar wind data alone and yet more applicable to the population as a whole than using just localized citizen science data. Such a system is also of great interest in the disaster warning and response community [*Tapia et al.*, 2014a, b; *Lalone et al.*, 2015].

2.3. Education and Outreach

The use of terminology in terrestrial and space weather forecasting is a difficult conundrum. Space weather forecasting is extremely complicated, with multiple threats manifesting at different times to multiple customers. Such forecasts are typically not written

for the general public and often include references to multiply defined scales of impacts, detailed observations, and model outputs without full explanation.

As one specific example, the NOAA geomagnetic storm scale [Poppe, 2000] is aimed toward federal stakeholders and large events (starting at G1 “minor”). A G1 geomagnetic storm corresponds to a Kp index of ~ 4 , and is appropriate on a global scale for most customers. However, at this level, aurora may be visible as far south as the US/Canadian border and absolutely spectacular in Alaska (not at all “minor” which communicates nearly insignificant).

Central tenets of scientific communication are simplification, accuracy, and commitment to communicating uncertainties. Examples used on Aurorasaurus include explaining that an aurora is not directly caused by the Sun and that solar predictions for auroral visibility are necessarily coarse with large uncertainties (especially in onset time).

Aurorasaurus aims to provide clear and low-jargon information about when, and where, an aurora is visible. In addition to plotting the modeled auroral oval on a map, real-time space weather data is provided to help our users understand how the drivers of an aurora vary with time. Rather than using abstract indices (e.g. Kp, Dst or AE) or describing the magnitude and orientation of the interplanetary magnetic field, to explain the strength of the drivers, we have opted to adopt and plot a measure of the “solar wind power”, a colloquial description of the epsilon coupling parameter [Perreault and Akasofu, 1978; Akasofu, 1981].

As shown in Figure 5, for a geomagnetic storm, the solar wind power can rise sharply to some maximum, indicating enhanced aurora at lower geomagnetic latitudes, and then decrease more slowly to background levels. The solar wind power has the benefit of

being expressed in the units of power (GW) - a concept the general public can easily understand. Although, admittedly not the highest correlating parameter with the auroral energy budget [Newell *et al.*, 2007], using the past hour's average of epsilon provides a simplified, accurate proxy for the auroral activity level (c.f. Akasofu [2015]) - thus meeting the central tenets of science communication [Case *et. al.*, manuscript in preparation, 2015].

To the public, the aurora often represents a beautiful but poorly understood phenomenon. Space plasma physics is not taught in most schools, including colleges, and most practitioners only enter the field in graduate school. The philosophy behind the educational offerings of the Aurorasaurus website are to offer engaging answers to common questions about the aurora.

Answers are provided in the form of Q&A sessions with members of the project's "scientist network" (facilitated through social media activities such as Reddit AMAs, Google+ Hangouts and Tweet Chats), FAQ web pages, and unique content such as Infographics. The scientist network is a globally distributed group of aurora/space weather experts who volunteer a modest amount of time for educational outreach.

Some space weather enthusiasts are self-taught and have a well-developed understanding of the aurora. For them, we offer a blog that features in-depth aurora-relevant space physics topics and an insight into the work of scientists studying the aurora. Blog posts are written by members of the Aurorasaurus core team, members of the Scientist Network and by guest authors. Social media updates about the blog drive traffic to the website and vice versa, a current best practice [Kietzmann *et al.*, 2011]. Partnering with the Scientists Network members' institutions to promote these pieces also helps to increase their visibility.

3. What is the relevance of Aurorasaurus to Solar-Terrestrial Physics?

Aurorasaurus has relevant applications to solar-terrestrial physics in several different areas: improving auroral oval forecast models by providing data for real-time validation, facilitating citizen science discoveries of unusual auroral types, improvement in our ability to image large storms, and as an opportunity to educate the public to our field.

There are several auroral oval models in the scientific literature, though perhaps the most widely-used is OVATION Prime [Newell *et al.*, 2010, 2014]. This model uses upstream solar wind data (i.e. ACE) as an input and is based upon functional fits to the solar wind coupling function $d\Phi_{MP}/dt$ [Newell *et al.*, 2007]. Aurorasaurus currently uses the University of Alaska Fairbanks (UAF) model (<http://www.gi.alaska.edu/AuroraForecast>), which is based upon the empirical model of Roble and Ridley [1987] and uses estimated real-time Kp as the input. The estimated real-time Kp, determined using ACE solar wind data, is provided by Wing *et al.* [2005].

There are several short-comings of solely using models for aurora prediction. For example, auroral oval models cannot yet account for substorms in which auroral activity can expand rapidly to lower latitudes for sub-hour time intervals. The models also currently rely on ACE real-time beacon data as the primary input, which are single point measurements on an aged satellite platform. Additionally, ACE solar wind speed measurements are somewhat limited and may be contaminated during solar energetic particle events (e.g. Baker *et al.* [2013]).

Auroral oval models currently lack real-time data for validation, especially for extreme auroral events. Filling in this gap is a goal of NASA Goddard's Community Coordinated Modeling Center (CCMC) [Zheng, 2014] and of the greater geospace research commu-

nity focused on model validation. This topic is important for space weather research-to-operations needs including scintillation and spacecraft charging [Zheng, pers. comm., 2014]. The collected citizen science data provide locations and times of auroral sightings as well as details such as the color, position in the sky, type, and movement of the aurora.

Citizen science has yielded unexpected discoveries (e.g. Lintott et al. [2009]) and such discoveries may be possible with auroral observations as well. Many users have high quality photography gear with GPS enabled devices. With a higher density of professional-quality observations it is possible to capture rare aurora at unusual places, possibly corresponding to the footprints of magnetospheric satellites, like RBSP, THEMIS, and GOES. Such conjunctions have made critical gains in field line mapping issues (e.g. Nishimura et al. [2010]; Weiss et al. [1992]).

Some of the outstanding problems of magnetospheric physics (namely that of substorm onset triggers and the space based origins of different types of aurora) could be greatly aided by more advantageous conjunctions and systematic work (e.g. [Donovan, E. pers. comm., 2014]; Borovsky [1993]).

Amateur ornithologists on eBird have reported confirmed sightings of extremely rare birds (e.g. Toochin and Levesque [2014]) and so the possibility of the amateur community finding a so-called “needle in the haystack” for aurora research is not insignificant. High latitude amateurs may be in a better position to observe substorm breakups for instance. Less spectacular phenomena like pulsating and diffuse aurora can also yield new insights when observed at unusual times or locations. Mid-latitude aurora and ionospheric disturbances are even more poorly characterized and understood.

As the gap between consumer and professional grade photographic equipment narrows, citizen scientist observers may be able to take a more scientific approach as well to observations, taking camera orientation and settings more quantitatively than qualitatively.

This is particularly useful since storm-time imaging of aurora over mid-latitudes is lacking, as we have been without high earth orbit imaging spacecraft for a decade. Most global scale images of auroral events (such as those captured by DE2) date back to the 1980's and a single pixel covered hundred of kilometers. Yet, there are many auroral features at a continuum of scales all the way down to sub-kilometer [*Stenbaek-Nielsen et al.*, 1998].

Low earth orbiting satellites can capture higher resolution data on segments of the auroral oval but data are not typically available in real-time, passes are separated by over an hour, and dedicated instruments are scarce. Recently, the ISS has used their imaging of the aurora to increase interest in the astronaut programs; however, without using additional software to deconvolve viewpoint and rapid motion, such photos cannot be used for scientific study.

Truly rare large events, such as the St. Patrick's Day storm [*Case et al.*, 2015b], could be widely captured with modern technology. With a globally distributed network of dedicated mid-latitude observers, stitching together a mosaic view of the aurora during a major geomagnetic storm may be possible. Space scientists need to know the global distribution and evolution of different types of aurora during storms to quantify the energy budget of these storms. This is a quite basic gap in knowledge, which leads to other gaps in understanding magnetosphere-ionosphere coupling. The ability to accurately model extreme events is hampered without this knowledge [*Ridley, pers. comm.*, 2013].

4. Early Results

Since its official launch in October 2014, Aurorasaurus has primarily been in a “data collection” and a “growth” mode. The number of registered users has been growing steadily as have the number of observations and verified tweets. One notable exception to this was a dramatic increase of registered users during the St. Patrick’s Day (17-19 March 2015) storm where the userbase increased by 50% in just one day [*Case et al.*, 2015b]. Total numbers, for the first six months, are shown in Table 1, and indicate strong growth for a new citizen science project.

As might be expected, the number of observations in a given day is predominantly dependent upon auroral activity. Figure 6 demonstrates that the number of observations (i.e. verified tweets and both positive and negative observations) generally peaks during days of enhanced geomagnetic activity (i.e. $K_p \geq 4$). The exact size of the peak is, of course, also dependent upon the number of registered users and so we might expect that the size of the peaks should increase as time goes on (even for similar-sized auroral events). The St. Patrick’s Day storm, however, shows a particularly large increase (approx. $10\times$ an “average” peak) in the number of observations reported to Aurorasaurus.

The vast majority of registered Aurorasaurus users are located in the USA (43%), Europe (42%) or Canada (13%). Other users are located in countries such as Australia, New Zealand and Russia among others. This distribution is perhaps not unexpected since the USA, Europe and Canada are all near the northern auroral oval (at least in part) and have relatively large English speaking (even if not native) populations. Our registered users provide good spatial resolution from approximately -170 to +40 degrees longitude, in the northern hemisphere.

The magnetic latitude of the positive aurora observations submitted to Aurorasaurus are shown in Figure 7. The locations have been collated into 1-degree bins and the colored stacked bars in each bin indicate the number of observations for each of the three Kp groups: $K_p \leq 4$ (green), $4 \leq K_p < 6$ (orange), and $K_p \geq 6$ (red). As expected, observations at lower magnetic latitudes generally occur during higher Kp values. Work into comparing these data with several auroral models, for the purposes of verification and validation, is underway.

5. Conclusion

This solar maximum has fundamentally different opportunities for engaging with the public than ever before: Facebook, Twitter, and many social media sites, did not exist during the last solar maximum. Digital cameras, along with smart phones and mobile applications, have improved significantly in this period which has fundamentally changed the way the public are able to capture rare events. When strong auroral displays do occur, the public records them, often in real-time, on a range of platforms (e.g. Facebook, Twitter and Flickr).

Citizen science projects have shown great success in many scientific disciplines. Aurorasaurus aims to further this success by building a new community of aurora-hunting citizen scientists, using intellectually engaging resources, aurora visibility alerts, and motivational incentives for participation. Early figures, as shown in Table 1, demonstrate that this relatively new project already has an active and engaged user base.

The Aurorasaurus team is actively working to grow this community to provide denser spatial coverage of aurora observers to both increase the number of notifications issued and the number of “ground-truth” observations. Citizen scientist recruitment and retention is

a challenge for many citizen science projects and so the scientific community is encouraged to join and raise awareness of this new project. Also welcome are additional Scientist Network outreach volunteers or scientific collaborators interested in exploiting the auroral observation data.

Aurorasaurus provides new tools to help aurora hunters observe the aurora and has demonstrated, during several auroral events in late 2014 and early 2015, that it is a responsive platform. The project's capability has been robustly designed to scale for larger events, such as the St. Patrick's Day storm, and more participants in the declining phase of this solar cycle.

Aurorasaurus aims to be a timely, agile software solution that provides a new data source for space weather activity. New capabilities will include improved auroral oval tools (including the aurora australis by using the publicly available OVATION Prime model) and more robust data assimilation techniques for nowcasting the visibility of the aurora. This extensible geosocial platform can be ported to other languages and phenomena thus creating tangible value to the emerging field of citizen science.

Auroras are more than just pretty pictures. There are many outstanding scientific mysteries to be explored by advancing the connection between space weather and auroras through citizen science. Aurorasaurus can improve the understanding of, and appreciation for, the dynamics and beauty of the aurora by the public and scientists alike.

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References

- Akasofu, S.-I. (1981), Energy coupling between the solar wind and the magnetosphere, *Space. Sci. Rev.*, *28*(2), 121–190.
- Akasofu, S.-I. (2015), Why does the aurora flare up?, *Eos*, *96*, doi:10.1029/2015EO027907.
- Barnard, L., et al. (2014), The Solar Stormwatch CME catalogue: Results from the first space weather citizen science project, *Space Weather*, doi:10.1002/2014SW001119.
- Baker, D. N., X. Li, A. Pulkkinen, C. M. Ngwira, M. L. Mays, A. B. Galvin, and K. D. C. Simunac (2013), A major solar eruptive event in July 2012: Defining extreme space weather scenarios, *Space Weather*, *11*, 585-591, doi:10.1002/swe.20097
- Borovsky, J. (1993), Auroral arc thicknesses as predicted by various theories, *J. Geophys. Res.*, *98*, 6101–6138.

Case, N. A., E. A. MacDonald, M. Heavner, A. H. Tapia, and N. Lalone (2015a), Mapping auroral activity with Twitter, *Geophys. Res. Lett.*, *42*, 3668–3676, doi: 10.1002/2015GL063709.

Case, N. A., E. A. MacDonald, K. G. Patel (2015b), St. Patrick's Day: a Success for Citizen Science, *Astronomy & Geophysics*, *56*(3), doi: 10.1093/astrogeo/atv089.

Clery D. (2011), Galaxy Zoo volunteers share pain and glory of research, *Science*, *333*, 173–175.

Coile, R. C. (1997), The role of amateur radio in providing emergency electronic communication for disaster management, *Disaster Prevention and Management: An International Journal*, *6*, 3, 176–185, doi:10.1108/09653569710172946

Cooper, S., F. Khatib, A. Treuille, J. Barbero, J. Lee, M. Beenen, A. Leaver-Fay, D. Baker, and Z. Popovic (2010), Predicting protein structures with a multiplayer online game, *Nature*, *466*, 756–760.

Crooks, A., A. Croitoru, A. Stefanidis, and J. Radzikowski (2013), # Earthquake: Twitter as a distributed sensor system, *Transactions in GIS*, *17*, 1, 124–147.

Culotta, A. (2010), Detecting influenza outbreaks by analyzing Twitter messages, *CoRR*, arXiv:1007.4748.

Danielsen, F., N. D. Burgess, P. M. Jensen, and K. Pirhofer-Walzl (2010), Environmental monitoring: the scale and speed of implementation varies according to the degree of people's involvement, *J. Appl. Ecol.*, *47*, 1166–1168.

Darg, D. W., S. Kaviraj, C. J. Lintott, K. Schawinski, J. Silk, S. Lynn, S. Bamford, and R. C. Nichol (2011), Galaxy Zoo: multi-mergers and the Millennium Simulation, *Mont. Not. R. Astron. Soc.*, *416*, 1745–1755.

D'Ignazio, Catherine, Rahul Bhargava, Ethan Zuckerman, and Luisa Beck (2014), CLIFF-CLAVIN: Determining Geographic Focus for News, *NewsKDD: Data Science for News Publishing*, at KDD 2014.

Earle, P., M. Guy, R. Buckmaster, C. Ostrum, S. Horvath, and A. Vaughan (2010), OMG earthquake! Can Twitter improve earthquake response? *Seismological Res. Lett.*, *81*, 2, 246–251.

Fore, L., K. Paulsen, and K. OLaughlin (2001), Assessing the performance of volunteers in monitoring streams, *Freshwater Biology*, *46*, 109–123.

Frissell, N. A., E. S. Miller, S. R. Kaeppler, F. Ceglia, D. Pascoe, N. Sinanis, P. Smith, R. Williams, and A. Shovkoplyas (2014), Ionospheric Sounding Using Real-Time Amateur Radio Reporting Networks, *Space Weather*, doi:10.1002/2014SW001132

Gugliucci, N., P. Gay, G. Bracey, I. Antonenko, S. Robbins, B. E. Schmidt, J. E. C. Scully, C. Lehan, and J. Moore (2014), Citizen Science with CosmoQuest: Science and Strategies, *Astronomical Society of the Pacific Conference Series*, *483*.

Howe, J. (2006), The Rise of Crowdsourcing, *Wired Magazine*, *14*(6), 1–4.

Kietzmann, J. H., K. Hermkens, I. P. McCarthy, and B. S. Silvestre (2011), Social media? Get serious! Understanding the functional building blocks of social media, *Business horizons*, *54*(3), 241–251, doi:10.1016/j.bushor.2011.01.005.

Kelling, S., W. M. Hochachka, D. Fink, M. Riedewald, R. Caruana, G. Ballard, and G. Hooker (2009), Data-intensive science: a new paradigm for biodiversity studies, *BioScience*, *59*, 613–620.

Knipp, D. (2015), Space Weather and Citizen Science, *Space Weather*, doi:10.1002/2015SW001167

Lalone, N., A. H. Tapia, N. A. Case, E. A. MacDonald, M. K. Hall, M. Heavner (2015), Hybrid Community Participation in Crowdsourced Early Warning Systems, Community Engagement in Crisis Informatics Research, in *Proceedings of the ISCRAM 2015 Conference*, in press.

Lampos, V., T. De Bie, and N. Cristianini (2010), Flu detector-tracking epidemics on Twitter, *Machine Learning and Knowledge Discovery in Databases*, 599–602, Springer, Berlin, Germany.

Lintott, C. J., et al. (2009), Galaxy Zoo: 'Hanny's Voorwerp', a quasar light echo?, *Mont. Not. R. Astron. Soc.*, 399, doi:10.1111/j.1365-2966.2009.15299.x

Lyons, W. A., T. A. Warner, S. A. Cummer, S. A. Rutledge, T. J. Lang, T. C. Meyer, G.

Lu, T. E. Nelson, and T. Samaras (2012), Different strokes: Researching the unusual lightning discharges associated with sprites and jets and atypical meteorological regimes, paper presented at the 22nd Intl. Lightning Detection Conf., Broomfield, CO, Vaisala, Inc.

Motoyama, M., B. Meeder, K. Levchenko, G. M. Voelker, and S. Savage (2010), Measuring online service availability using twitter, WOSN10, 13-13.

Newell, P. T., T. Sotirelis, K. Liou, C.-I. Meng, and F. J. Rich (2007), A nearly universal solar wind-magnetosphere coupling function inferred from 10 magnetospheric state variables, *J. Geophys. Res.*, 112, A01206, doi:10.1029/2006JA012015.

Newell, P. T., T. Sotirelis, and S. Wing (2010), Seasonal variations in diffuse, monoenergetic, and broadband aurora, *J. Geophys. Res.*, 115, A03216, doi:10.1029/2009JA014805.

- Newell, P. T., K. Liou, Y. Zhang, T. Sotirelis, L. J. Paxton, and E. J. Mitchell (2014), OVATION Prime-2013: Extension of auroral precipitation model to higher disturbance levels, *Space Weather*, *12*, 368–379, doi:10.1002/2014SW001056.
- Nishimura, Y., et al. (2010), Identifying the Driver of Pulsating Aurora, *Science*, *330*, 6000, 81–84, doi: 10.1126/science.1193186.
- Perreault, P., and S-I Akasofu (1978), A study of geomagnetic storms, *Geophys. J. R. Astron. Soc.*, *54*, 547–573.
- Poppe, B. B. (2000), New scales help public, technicians understand space weather, *Eos Trans. AGU*, *81*(29), 322–328, doi:10.1029/00EO00247.
- Priedhorsky, R., E. A. MacDonald, and Y. Cao (2012), First solar maximum with social media: can space weather forecasting be improved?, EOS Trans. AGU Fall Meeting.
- Reges, H. W., R. C. Cifelli, N. J. Doesken, and J. Turner (2008), CoCoRaHS (the Community Collaborative Rain, Hail and Snow network) - the accidental network: evolving collaborations, in *17th Symposium on Education*, American Meteorological Society.
- Roble, R. G., and E. C. Ridley (1987), An auroral model for the NCAR thermospheric general circulation model (TGCM), *Ann. Geophys.*, *5*, 369–382.
- Sakaki, T., M. Okazaki, and Y. Matsuo (2010), Earthquake shakes Twitter users: real-time event detection by social sensors, in *Proceedings of the 19th international conference on World Wide Web*, 851–860.
- Shirky, C. (2010), *Cognitive Surplus: Creativity and Generosity in a Connected Age*, The Penguin Press HC, ISBN-10: 1594202532.
- Silverman, S.M., and D. C. Blanchard (1983), Wilson Bentleys Auroral Observations, *Planet. Space Sci.*, *31*, 10.

Smith, A. M., S. Lynn, and C. J. Lintott (2013), An introduction to the zooniverse, presented at First AAAI Conference on Human Computation and Crowdsourcing.

Stenbaek-Nielsen, H. C., T. J. Hallinan, D. L. Osborne, J. Kimball, C. Chaston, J. McFadden, G. Delory, M. Temerin, and C. W. Carlson (1998), Aircraft observations conjugate to FAST: Auroral arc thickness, *Geophys. Res. Lett.*, *25*, 2073–2076.

Sullivan, B., C. Wood, M. Iliff, R. Bonney, D. Fink, and S. Kelling (2009), eBird: A citizen-based bird observation network in the biological sciences, *Biological Conservation*, *142* (10), 2282–2292.

Sutton, J., L. Palen, and I. Shklovski (2008), Backchannels on the front lines: Emergent uses of social media in the 2007 southern California wildfires, Proceedings of the 5th International ISCRAM Conference, 624–632.

Tapia, A. H., K. Bajpai, B. J. Jansen, and J. Yen (2011), Seeking the Trustworthy Tweet: Can Microblogged Data Fit the Information Needs of Disaster Response and Humanitarian Relief Organizations, in *Proceedings of the 8th International ISCRAM Conference*, Lisbon, Portugal.

Tapia, A. H., N. LaLone, E. A. MacDonald, M. Hall, N. A. Case, and M. Heavner (2014a), AURORASURUS: Citizen Science, Early Warning Systems and Space Weather, in *Second AAAI Conference on Human Computation and Crowdsourcing*, pp.30–32, doi:10.13140/2.1.4865.0563.

Tapia, A. H., N. LaLone, E. A. MacDonald, R. Priedhorsky, and M. Hall (2014b), Crowdsourcing Rare Events: Using Curiosity to Draw Participants into Science and Early Warning Systems, in *Proceedings of the 11th International ISCRAM Conference*, University Park, Pennsylvania, USA.

Toochin, R. and P. Levesque (2014), A Eurasian Hobby (*Falco subbuteo*) observation in Sooke: A Second Sight Record for British Columbia, report, E-Fauna BC, University of British Columbia, Canada

Trumbull, D. J., R. Bonney, D. Bascom, and A. Cabral (2000), Thinking scientifically during participation in a citizen-science project, *Science Education*, 84, 265–270.

Vieweg, S., A. L. Hughes, K. Starbird, and L. Palen (2010), Microblogging during two natural hazards events, in *Proceedings of the 28th international conference on Human factors in computing systems - CHI '10*, New York, New York, USA.

Walker, C. E., S. M. Pompea, and D. Isbell (2008), GLOBE at Night 2.0: On the Road Toward IYA 2009, presented at EPO and a Changing World: Creating Linkages and Expanding Partnerships, 389, 2008.

Weiss, L. A., P. H. Reiff, R. V. Hilmer, J. D. Winningham, and G. Lu (1992), Mapping the Auroral Oval into the Magnetotail Using Dynamics Explorer Plasma Data, *J. Geomag. Geoelectr.*, 44, 1121–1144, doi:10.5636/jgg.44.1121

Wiggins, A., and K. Crowston (2010), Developing a Conceptual Model of Virtual Organizations for Citizen Science, *International Journal of Organisational Design and Engineering*, 1(1/2), 148–162, doi:10.1504/IJODE.2010.035191.

Willett, W., P. Aoki, N. Kumar, S. Subramanian, and A. Woodruff (2010), Common sense community: scaffolding mobile sensing and analysis for novice users, *Lect. Notes Comput. Sci.*, 301–318.

Wing, S., J. R. Johnson, J. Jen, C.-I. Meng, D. G. Sibeck, K. Bechtold, J. Freeman, K. Costello, M. Balikhin and K. Takahashi (2005), Kp forecast models. *J. Geophys. Res.*, 110, A04203, doi:10.1029/2004JA010500.

Wood, C., B. Sullivan, M. Iliff, D. Fink, and S. Kelling (2011), eBird: Engaging birders in science and conservation, *PLoS Biology*, 9 (12).

Yu, J., S. Kelling, J. Gerbracht, and W. K. Wong (2012), Automated data verification in a large-scale citizen science project: A case study, in *E-Science (e-Science), 2012 IEEE 8th International Conference on*, pp. 1–8, doi:10.1109/eScience.2012.6404472

Zheng, Y. (2014), Report on study of auroral oval boundaries, Modeling challenges in auroral region, 2014 GEM Mini-Workshop, Portsmouth, Virginia, US.

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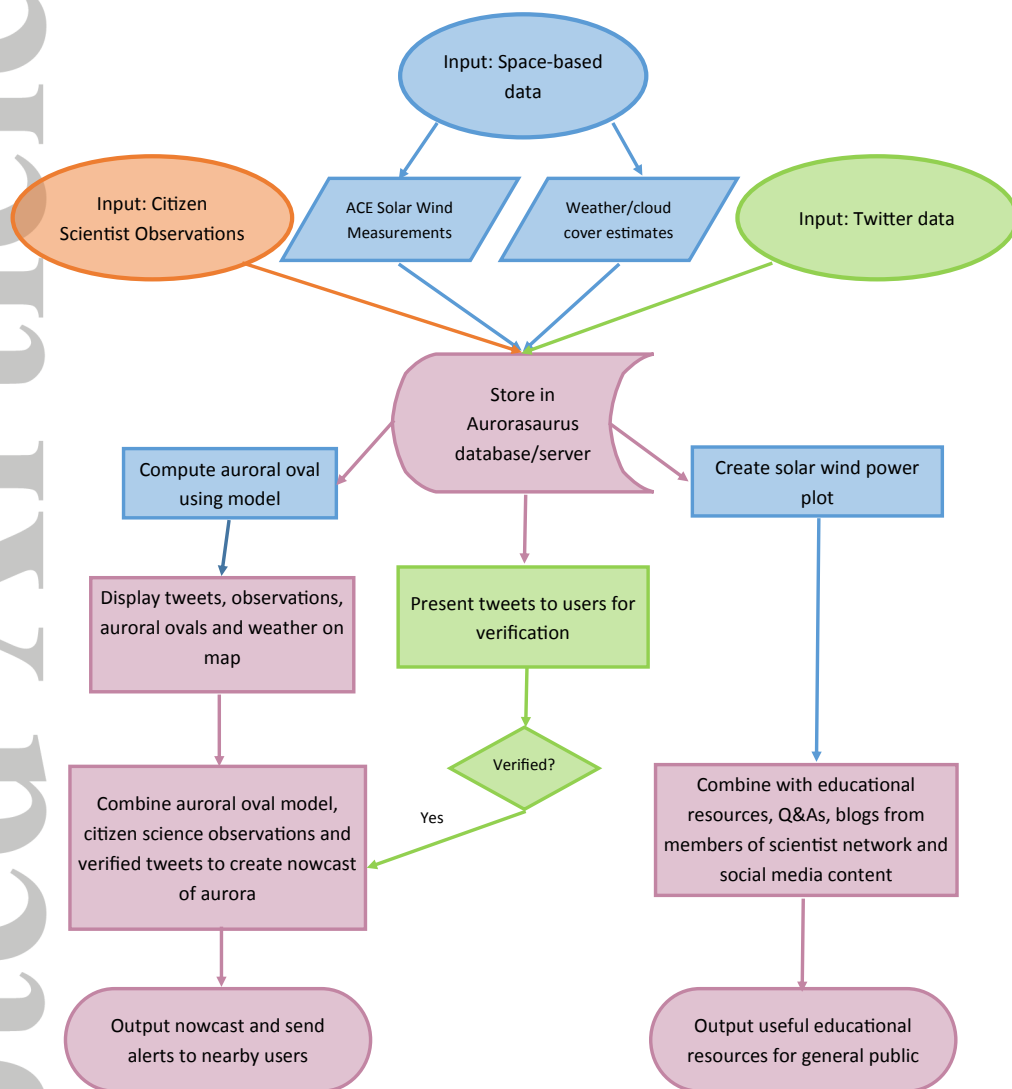


Figure 1. A flow chart demonstrating the different data inputs/outputs (ovals) and processes (rectangles) of the Aurorasaurus project. The blue filled shapes indicate usage of space-based data, orange indicates citizen science data and green indicates Twitter data. The purple shapes indicate a combination of several data sources. All data sources are fed into the Aurorasaurus database and are then processed in several different ways.

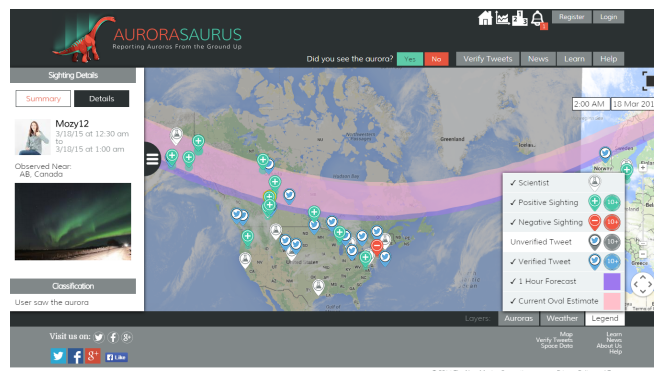


Figure 2. A screen capture of the main Aurorasaurus page is shown (02:00 EDT, 18 March 2015). (bottom right) The legend includes on/off toggles for: the current and forecast auroral ovals, citizen observations, and tweets relating to the aurora. (top right) The site navigation icons indicate (from left to right) the Home screen, a real-time plot of the epsilon solar wind power parameter, the Leaderboard of participants, and notifications for registered users. (middle left) Also shown are the sighting details for a positive sighting report (green + icon).

The image shows a screenshot of the Aurorasaurus website interface. On the left, there are two 'Sighting Details' panels. The top panel shows a report for a user named 'Suzie' on 11/16/14, observed near AK, United States, with the classification 'User saw the aurora'. The bottom panel shows the same report with more details: 'Colors Seen: Green', 'Types of Aurora Seen: Diffuse Glow', 'Height in Sky: Northern horizon only', and 'How Active: Quiet, not moving much'. On the right is a 'Make a Report' form. The form fields include: 'Location: Alaska, USA', 'When did your observation start? 16 Nov 2014 1:30 AM', 'When did your observation end? 16 Nov 2014 1:45 PM', 'Ongoing? []', 'What colors did you see? [] Red [x] Green [] White [] Pink', 'Other: Another color? []', 'What type of aurora did you see? [] Discrete Arcs [x] Diffuse Glow [] Patches (pulsating) []', 'Other: Something different? []', 'Where in the sky was the aurora? Northern Horizon Only []', and 'Other: []'.

Figure 3. An example of a citizen scientist’s aurora sighting report. The two boxes on the left (both with header “Sighting Details”) show the report as it appears on the Aurorasaurus site; the large box on the right (header “Make a Report”) shows the sighting report submission form.

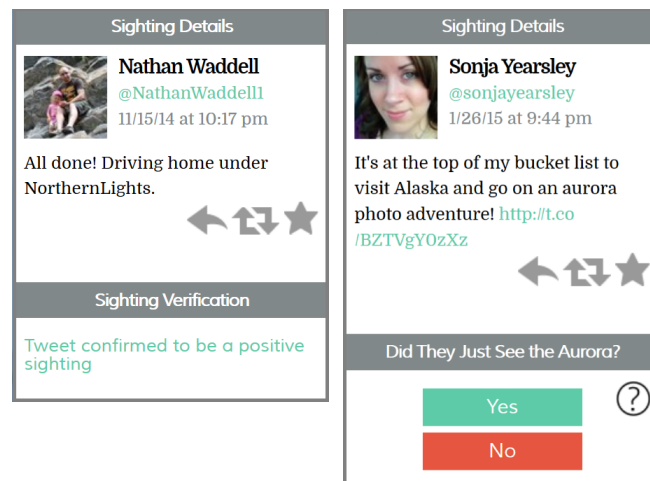


Figure 4. (left) An example of a positive aurora sighting tweet and (right) an example of an aurora-related but non-sighting tweet. Crowdsourcing is used to identify genuine, real-time, aurora observations.

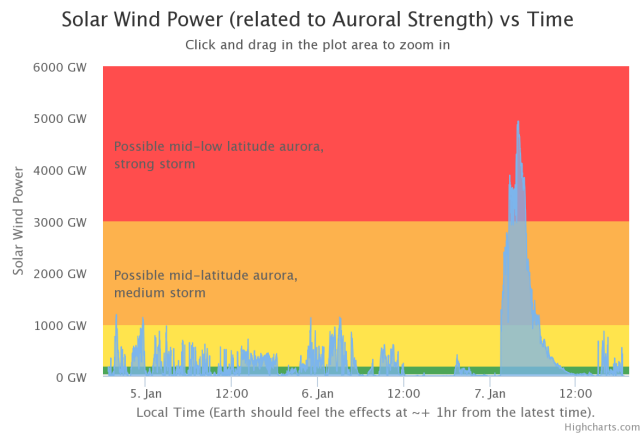


Figure 5. An example of the solar wind power plot on the Aurorasaurus website (5-7 January 2015). The “power” is in fact the value of the epsilon coupling function and is calculated in real-time using upstream solar wind data from ACE. The chart has several color bands to indicate the possible latitude from which an aurora might be visible.

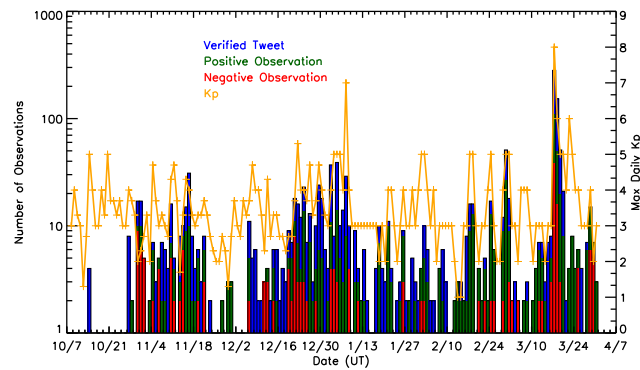


Figure 6. A stack plot of the Aurorasaurus citizen science data over for a period spanning six months (October 2014 - March 2015). The number of observations (verified tweet - blue, positive sighting - green and negative sighting - red) per day is plotted on a logarithmic scale. Plotted on the secondary y-axis is the maximum daily Kp value (a quasi-logarithmic scale of geomagnetic activity).

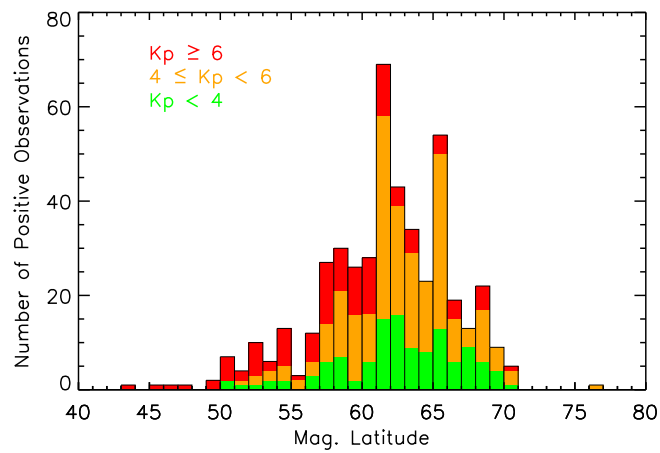


Figure 7. A stack plot of the magnetic latitude of the Aurorasaurus positive aurora observations for the same six month period as Figure 6. The number of positive observations per one degree latitude bin is stacked and colored based upon the K_p level during the observation.

Table 1. A List of Aurorasaurus Resources and Useful Figures¹

Resource	URL	Figures
Website	www.aurorasaurus.org	~2,000 registered users ~1,050 sighting reports ~1,750 verified tweets
Mobile apps (iOS & Android)	www.aurorasaurus.org (from a mobile device)	~3,000 downloads
Facebook	www.fb.com/aurorasaurus.org	~19,000 likes
Twitter	www.twitter.com/tweetaurora	~1,100 followers
Scientist Network	www.aurorasaurus.org/about-us	13 members
Email	aurorasaurus.info@gmail.com	
Blog	blog.aurorasaurus.org	

¹ Figures accurate as of July 2015.