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Chapter 8

Citizen Science in Astronomy Education

Laura Trouille, Thomas Nelson, Julie Feldt, John Keller, Marc Buie, Carie Cardamone, Bethany Cobb Kung, Karen Masters, Kate Meredith and Kelly Borden

Citizen science has proven to be a unique and effective tool in helping science and society cope with the ever-growing data rates and volumes that characterize the modern landscape. It also serves a critical role in engaging the public with research in a direct, authentic fashion, and by doing so promotes a better understanding of the processes of science. As the field of citizen science matures, there are a growing number of quality opportunities for instructors to engage their students in authentic research through citizen science. Citizen science in classroom settings provides unique opportunities to engage students in the process of scientific discovery while making real and valued scientific contributions and is well aligned with research-supported educational practices. In this chapter, we provide a brief overview of the history and current state of citizen science and highlight a few key results from the literature around the impact of engagement in citizen science on learning and attitudes. We then present case studies of curricula incorporating citizen science into undergraduate introductory astronomy courses for non-STEM majors (i.e., Astro 101). This article is not meant to provide an exhaustive list of existing efforts; rather, we focus on two specific citizen science approaches and platforms: online data processing through Zooniverse and data gathering and analysis through the Research and Education Collaborative Occultation Network (RECON). We hope these examples serve as inspiration for joining the growing community of instructors bringing citizen science into their classrooms.

Chapter Objectives

By the end of the chapter, readers will be able to

- describe the breadth and diversity of citizen science opportunities available for instructors and their students,

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- give examples and best practices to follow in incorporating citizen science into their classrooms, and
- discuss the literature around the positive impacts of incorporating citizen science in the classroom, as well as the open questions and opportunities for further research.

8.1 Overview

Citizen science—the involvement of the general public in research—has a long history. An early example is Edmund Halley's study of timings during the 1715 total solar eclipse, which included observations from a distributed, self-organized group of observers (Pasachoff 1999). Works by Dawson et al. (2015) and Shuttleworth (2018), among others, have linked modern-day efforts to their 19th century antecedents, for example, highlighting the role played by networks of amateur meteorological observers in establishing that field of study (i.e., by 1900, more than 3400 observers were contributing data to a network organized by George Symons, producing data on a scale that could not be matched by the professional efforts of the time).

In recent decades, citizen science has gained renewed prominence, boosted in part by technological advances and digital tools like mobile applications, cloud computing, and wireless and sensor technology, which have enabled new modes of public engagement in research (Bonney et al. 2016) and facilitated research projects that investigate questions from data at scales beyond the professional research community's resource capacity (Miller-Rushing et al. 2012).

In 2015, professional citizen science organizations were created in Europe, Australia, and the United States. In the U.S., the Crowdsourcing and Citizen Science Act of 2015 was introduced to encourage the use of citizen science within the federal government and, that same year, the first Citizen Science Association Conference was held (though some consider the 2012 European Space Agency side event on citizen science the first CSA gathering). CitizenScience.gov currently lists over 400 active citizen science projects. Participation in citizen science today ranges from hands-on data collection, tagging, analysis, and research projects (e.g., iNaturalist.org, Laurie 2018; eBird.org, Sullivan et al. 2009; and CitSci.org, Wang et al. 2015) to contributing in-person data and participating in hands-on data analysis (e.g., the Denver Museum of Science Genetics of Taste Lab, Boxer & Garneau 2015) to a growing number of co-created environmental monitoring projects using low-cost sensors with community members working in collaboration with researchers (e.g., the LA Watershed Project[1]) to online data processing efforts, of which Zooniverse.org is one example and described in more detail below.

Online citizen science, which has become a proven method of distributed data analysis, enables research teams from diverse domains to solve problems involving large quantities of data, taking advantage of the inherently human talent for pattern recognition and anomaly detection. For example, the EternaGame.org

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[1] https://www.epa.gov/urbanwaterspartners/diverse-partners-brownfields-healthfields-la-watershed.

(Lee et al. 2014) online gaming environment (which is the next generation of the FoldIT platform; Cooper et al. 2010) challenges players to design new ways to fold RNA molecules to find solutions for diseases like tuberculosis. These new molecular structures are then synthesized and tested in Stanford's medical labs. As another example, Eyewire (Kim et al. 2014) and their recently released NEO online citizen science game connects citizen science with data collected by the Allen Institute for Brain Science and Baylor College of Medicine as part of the Intelligence Advanced Research Projects Activity's Machine Intelligence from Cortical Networks program (MICrONs). There are also growing numbers of online crowdsourced transcription efforts in the humanities, including From the Page,[2] Veridian (Daniels et al. 2014), Smithsonian Transcript Center,[3] and Transcribe Bentham (Causer et al. 2018). Furthermore, while not the focus of this chapter, we note the parallel track of "volunteer/distributed computing" efforts, like SETI@Home,[4] which harness computing resources for distributed computing and/or storage.

Within this growing citizen science ecosystem, astronomy has had a long history of leadership, as noted above. This leadership has continued into recent decades with the great breadth and depth of projects available. In the remainder of this chapter, we will focus on efforts through Zooniverse and RECON, but we wanted to provide a list of other astronomy-related citizen science platforms and programs here and strongly encourage readers to explore the myriad of opportunities available:

- Aurorasaurus—NASA (http://aurorasaurus.org/).
- Cameras for All-Sky Meteor Surveillance [CAMS]—SETI Institute (http://cams.seti.org).
- Citizen CATE—National Solar Observatory (https://eclipse2017.nso.edu/citizencate).
- Cosmoquest—(https://cosmoquest.org).
- Distributed Electronic Cosmic-Ray Observatory (https://wipac.wisc.edu/deco/app).
- Globe at Night—National Optical Astronomy Observatory (https://www.globeatnight.org).
- QuarkNet (https://quarknet.org).
- Radio JOVE—NASA (https://radiojove.gsfc.nasa.gov).

See CitizenScience.gov and SciStarter.org for comprehensive listings of citizen science projects and platforms not only in astronomy but also across the disciplines.

In parallel with this renaissance in citizen science efforts, there has been an explosion in citizen science efforts carried out in formal classroom settings. Citizen science provides unique, hands-on opportunities to engage students in the process of scientific discovery while making real and valued scientific contributions and is well aligned with research-supported educational practices (Jones et al. 2010; PCAST 2012; Freeman

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[2] https://fromthepage.com.

[3] https://siarchives.si.edu/collections/siris_sic_14645.

[4] https://setiathome.berkeley.edu.

et al. 2014). In geoscience and biology courses for majors, there is a strong tradition of incorporating research experiences where the students efforts feed into a larger, existing citizen science project (e.g., CASPiE, Quardokus et al. 2012; Genome Education Partnership, Shaffer et al. 2014; Sea-Phages, Caruso et al. 2009; eternaGame.org; fold. It; eBird: Surasinghe & Courter 2012; etc.). There is also a growing number of citizen-science-based research experiences in non-major geoscience, biology, and astronomy courses (e.g., Trautmann 2013; Dickinson et al. 2012; smallWorldInitiative.org; citizen-science-integrated biology courses at Brandeis, University of Delaware's water biomonitoring efforts, etc.) and broader cross-campus initiatives (e.g., citizenscience.bard.edu). In Astro 101, a notable example is Slater et al.'s use of a backwards faded scaffolding approach in which students carry out multiple citizen-science-based mini inquiries throughout the semester (Slater et al. 2011).

Numerous studies have outlined the positive impacts of public participation in scientific research, including increases in long-term environmental, civic, and research interests (e.g., Dickinson & Bonney 2012 and references therein); the empowerment of communities to influence local environmental decision-making (Dickinson & Bonney 2012; Newman et al. 2012); the increased representation of women and minorities in the scientific process (Groulx et al. 2017); increases in confidence (Raddick et al. 2010, 2013; Masters et al. 2016; Greenhill et al. 2014), scientific literacy (Cronje et al. 2011; Crall et al. 2013; Jones et al. 2016; Trumbull et al. 2000), domain knowledge (Brossard et al. 2005; Masters et al. 2016); and increases in understanding that scientific progress is a collective process (Ruiz-Mallén et al. 2016).

In the sections below, we describe a few examples of the use and impact of citizen science in formal astronomy classroom environments. This article is not meant to provide an exhaustive list of existing efforts; rather, our goal with sharing these few examples is to provide an inspiration point for others to build from. Along these lines, we have chosen two different citizen science approaches from which to pull examples: (1) Zooniverse, an online platform for data processing and analysis, and (2) RECON, a coordinated telescope observing network for data gathering.

8.2 Astro 101: Zooniverse-based Citizen Science Opportunities

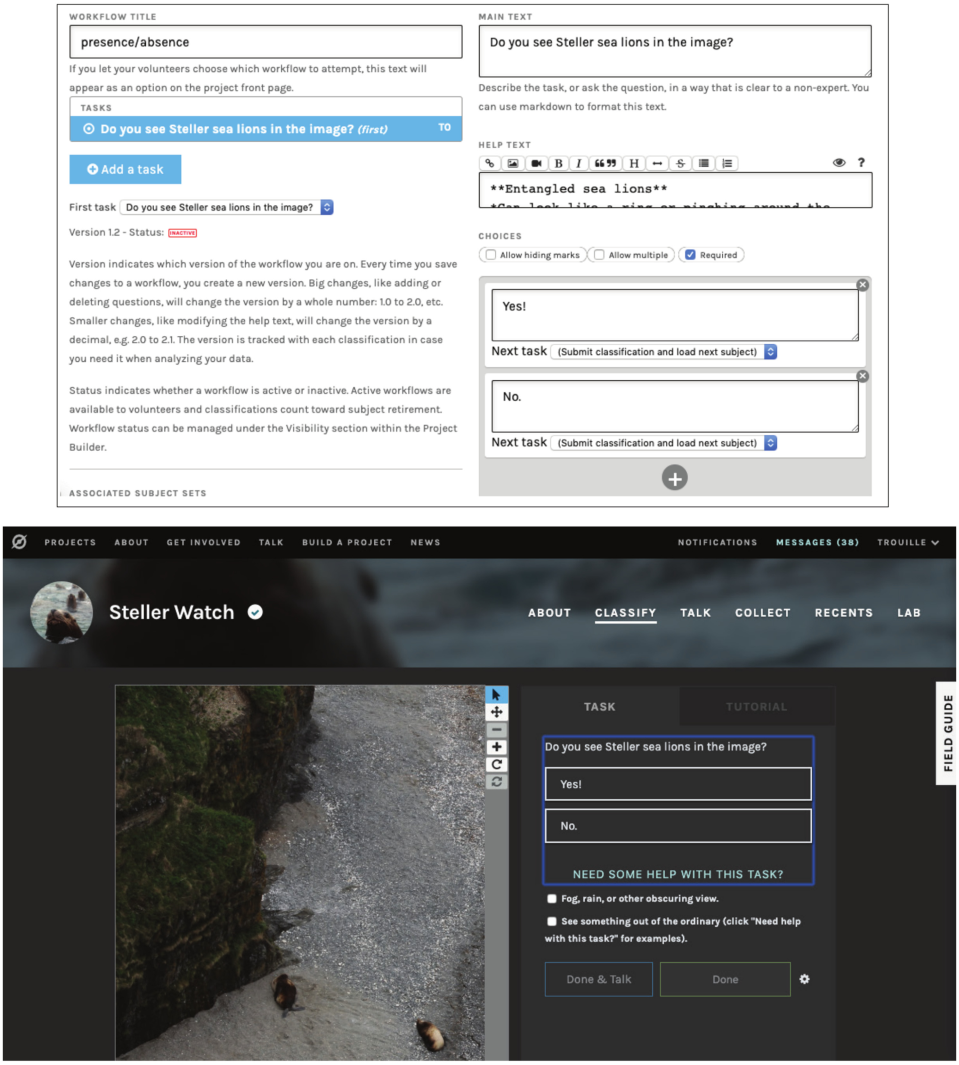
There is a critical need to support the development of a scientifically and data literate society, crucial to our country's health and economy (National Research Council 1996, 2003, 2010). Each year hundreds of thousands of non-science majors take introductory astronomy courses (Fraknoi 2001; Chen & Solder 2013) to fulfill their science requirement for graduation. These students later take on a range of roles in society, from lawyers to teachers and community leaders to policy makers. Introductory science courses like Astro 101 are often these students' last formal exposure to science, yet they generally provide little insight into how science actually works or exposure to key 21st century skills of data handling and analysis. Scientific literacy and data literacy skills serve non-STEM majors by empowering them to feel confident using evidence-based reasoning to solve personally meaningful problems in their everyday lives: when reading the news, voting on policy decisions that impact them and their communities, etc. (Feinstein et al. 2013). Introductory science courses like Astro 101 are also often the last formal opportunity for science identity development and positive impacts on attitudes toward science and scientists. In the subsections below, we first provide details on the Zooniverse platform and then describe two models for engaging Astro 101 students in citizen science through Zooniverse.

8.2.1 Zooniverse

Zooniverse.org is the largest platform for online citizen science, host to over 80 active projects with 1.7 million registered participants around the world. It is unique among online citizen science platforms as a result of its (1) shared open-source software, experience, expertise, and input from users across the disciplines, (2) reliable, flexible, and scalable application programming iInterface (API), which can be used for a variety of development tasks, (3) free, do-it-yourself (DIY) "Project Builder" (also known as the Project Builder Platform) capabilities as described below, and (4) the scale of its existing audience. Zooniverse partners with hundreds of researchers across many disciplines, from astronomy to zoology, cancer research to climate science, history to the arts. At a time when citizen science is gaining prominence across the world, Zooniverse has become a core part of the research infrastructure landscape. Since the launch in 2007 of the Galaxy Zoo project (Lintott et al. 2008; Fortson et al. 2012), Zooniverse projects have led to over 150 peer-reviewed publications, enabling significant contributions across many disciplines, such as in ecology (Swanson et al. 2016; Matsunaga et al. 2016; Arteta et al. 2016; Anderson et al. 2016), humanities (Williams et al. 2014; Grayson 2016), biomedicine (dos Reis et al. 2015), physics (Barr et al. 2016; Zevin et al. 2017), climate science (Hennon et al. 2015), and astronomy (Lintott et al. 2008; Fortson et al. 2012; Johnson et al. 2015; Marshall et al. 2015; Schwamb et al. 2018).

Thus, these projects have established a track record of successfully engaging a disparate crowd of volunteers and producing reliable results used by the wider scientific community. We note that lack of specialist knowledge or misclassification can lead to errors within data produced by citizen scientists (Freitag et al. 2016). In the Zooniverse model, however, consensus results are created based on numerous classifications (e.g., 15+ individuals classify each subject), which mitigate the impact of any one individual's errors. A rigorous approach to assessing and ensuring data quality within citizen science projects is particularly important when those data are used in a classroom context. Mitchell et al. (2017) found that in undergraduate use of the Australian phenology citizen science program, ClimateWatch, only 31% of students agreed with the statement that "data collected by citizen scientists are reliable" at the end of the project, whereas the rate of agreement was initially 79%. This result is particularly harmful in a society where science is already widely mistrusted and the processes of science are misunderstood.

The number of projects supported by Zooniverse has recently experienced rapid growth, an acceleration that is the result of the launch in July 2015 of the free Project Builder Platform (zooniverse.org/lab), which enables anyone to build and deploy an online citizen science project at no cost, within hours, using a web browser-based toolkit. The Project Builder supports the most common types of interaction, including classification, multiple-choice questions, comparison tasks, and marking and drawing tools. Figure 8.1 provides screenshots of the Project Builder editor interface and an example of the resulting public-facing web page. The Project Builder front-end is a series of forms and text boxes a researcher fills out to create the project's classification interface and website. All Project Builder projects come with a landing page, classification interface, discussion forum, and "About" pages for



WORKFLOW TITLE

presence/absence

If you let your volunteers choose which workflow to attempt, this text will appear as an option on the project front page.

TASKS

Do you see Steller sea lions in the image? *(first)*

First task: Do you see Steller sea lions in the image?

Version 1.2 - Status: INACTIVE

Version indicates which version of the workflow you are on. Every time you save changes to a workflow, you create a new version. Big changes, like adding or deleting questions, will change the version by a whole number: 1.0 to 2.0, etc. Smaller changes, like modifying the help text, will change the version by a decimal, e.g. 2.0 to 2.1. The version is tracked with each classification in case you need it when analyzing your data.

Status indicates whether a workflow is active or inactive. Active workflows are available to volunteers and classifications count toward subject retirement. Workflow status can be managed under the Visibility section within the Project Builder.

ASSOCIATED SUBJECT SETS

MAIN TEXT

Do you see Steller sea lions in the image?

Describe the task, or ask the question, in a way that is clear to a non-expert. You can use markdown to format this text.

HELP TEXT

```
**Entangled sea lions**
```

CHOICES

☐ Allow hiding marks ☐ Allow multiple ☑ Required

Yes!

Next task: (Submit classification and load next subject)

No.

Next task: (Submit classification and load next subject)

Steller Watch

Do you see Steller sea lions in the image?

Yes!

No.

☐ Fog, rain, or other obscuring view.

☐ See something out of the ordinary (click "Need help with this task?" for examples).

Figure 8.1. Screenshots of Zooniverse's free Project Builder Platform. The first image shows the project builder interface. The second image shows the website the project builder can immediately view as they upload their content. Credit: Zooniverse.

content about the research, the research team, and results from the project. The Project Builder is transformative; prior to its development, a typical online citizen science project required months to years of professional web development time. Zooniverse went from launching 3–5 projects a year to launching 26 in 2016, 44 in 2017, and over 50 in 2018.

Within the landscape of citizen science use in formal classroom environments, Zooniverse has two key characteristics we take advantage of here: (1) an extremely low barrier to entry and (2) projects across the disciplines that produce quality data that are easy to understand and use. In many citizen science projects and approaches, instructors must spend considerable time and effort training students so that they are able to make meaningful and quality contributions. In contrast, a student can provide useful and valued classifications to a Zooniverse project within minutes of entering the site. In terms of ease of access, by working within an online citizen science platform, we provide a complementary approach to field-work-based citizen science experiences. Through Zooniverse, students can contribute to the data processing, gain access to the classification results and additional relevant metadata, and pursue research projects in the context of professional researchers actively working with those same data. This removes geographic barriers as well as resource constraints for institutions with limited access to active researchers and/or who are unable to sustainably carry out field work.

8.2.2 Improving Student Attitudes toward Science with a Citizen Science Assignment

Students in introductory science classrooms often feel that they inherently lack the ability to "do science." We frequently hear students in introductory astronomy label themselves as "not a science (or math) person." It is also not uncommon for students to admit that they have "always been bad at science" or simply state that they "don't like science." The cause of these negative attitudes toward personal scientific proficiency are, of course, complex and can vary by the individual student (Osborne et al. 2003). Many students will have struggled with content in previous science and mathematical courses and, therefore, enter the college-level introductory science classroom having already developed an unfortunate aversion to science and strong doubts about their own scientific capabilities. Furthermore, such students are often in our classrooms not because of any innate interest in the subject matter but, instead, because general curricular requirements dictate that students must complete a science course in order to graduate.

How can we challenge and stretch our students while simultaneously bolstering their scientific self-confidence and repairing their attitudes toward science in general? Citizen science engages people without any specialized knowledge to take part in scientific research and highly values their contributions. This means that even students in an introductory science course can contribute to real scientific research studies. This contrasts with typical introductory science laboratory exercises in which students either simply reproduce well-known results or conduct more independent research projects which, however, do not produce results that contribute to general scientific knowledge (because they are only "published" in class and/or because the scope of such projects is highly limited by both student expertise and time). Students can easily differentiate between authentic and inauthentic work, and we hypothesized that students would have a positive reaction to engaging in authentic science through citizen science. Below we describe one model for engagement with online citizen science and the resulting impact on attitudes.

It is worth noting that developing authentic projects for the introductory classroom from scratch is incredibly challenging and time consuming, so much so that it is an unrealistic prospect for many faculty members. Because the citizen science projects on mature platforms such as Zooniverse have already been developed and vetted (as well as maintained) by other scientists, citizen science can be leveraged by any faculty member to quickly and easily bring authentic scientific research into the introductory science classroom.

Example: Low-barrier Approach to Citizen Science in Astro 101. With these goals in mind, authors Cardamone and Cobb Kung developed a Zooniverse-based citizen science student assignment to be completed by students primarily outside of class time over the period of about one month, with the expectation that students would spend between 5 and 10 total hours on the project during that month. The assignment was used in a number of introductory astronomy courses at George Washington University (Washington, DC) and Wheelock College (Boston, MA), with class sizes ranging from about 15 to 60 students. A similar assignment, however, could be used in any introductory science course, regardless of topic or class size.

Curricular design. The assignment required each student to individually contribute to a Zooniverse project over approximately four weeks and to briefly reflect on those contributions. Meanwhile, the students worked in peer groups to understand and articulate the scientific purpose of a common citizen science project. The assignment was introduced in class by describing how citizen science allows for the collaboration between professional scientists and the wider public. Connections were made to how these collaborations enable new scientific research and discoveries, and improve public understanding of both science and the scientific process. It was emphasized that everyone can participate in citizen science, as the projects are designed so that no specialized knowledge or skills are required. Indeed, citizen science harnesses the unique power and creativity of the human brain unmatched by even the best computers to recognize patterns and anomalies. Finally, students were told that they would be contributing directly to ongoing scientific research by participating in a citizen science project of their choice.

The students begin working on the assignment by exploring and then selecting a Zooniverse project in the "physics" or "space" categories (see Zooniverse.org/projects). They were limited to these general categories due to the topic of the courses, but as the Zooniverse hosts projects across the disciplines—including biology, climate change, nature, medicine, history, and social science—the assignment can be utilized in many different types of introductory science courses. Students could choose a particular Zooniverse project that was most aligned with their interests and values to provide them with a sense of agency and to increase their motivation in participating in the project (Christenson et al. 2012). Project choices were limited to those less than 50%

completed, so that it was likely to continue running for the entire time period of the assignment. Once students had individually selected a project, they formed groups of approximately four students around their shared interest in contributing to a particular Zooniverse project. The students were also encouraged at this early stage to begin to explore the science background of the project and its specific scientific goals.

Over the ~4 weeks of the assignment, students worked individually, making multiple visits to Zooniverse to contribute to their project. Students contributed to their project a minimum of eight times, ideally visiting the citizen science project two to three times per week, with each visit being approximately 15 minutes in length, but no two visits being on the same day. This assignment can be modified to be completed in shorter or longer time spans and require more or fewer visits, though we would encourage students to be required to make at least five visits because most students took several visits to become accustomed to their projects and confident in their classification abilities. Students kept a log of their work, recording visit dates and start/stop times, as well as a brief reflection for each visit. They were encouraged to note images or data they encountered that were particularly interesting, surprising, or confusing. Reflections were only required to be a few sentences in length, though some students were quite verbose. Some students kept these logs electronically, while others logged their visits on paper. Once they had completed their visits, students were asked to take a screenshot of their Zooniverse "recent projects" page that showcased the overall number of classifications they contributed to the project.

The project culminated with each student group producing a creative video presentation demonstrating their understanding of their particular Zooniverse project. Students were encouraged to use any video technique they found most appealing, including filming themselves, making animations, or providing narration over images. Students were required to answer four key questions with the video: (1) What are the overarching science goals that the citizen science project is trying to achieve? (2) What was the specific task (or tasks) that you did as a participant in this project? Reflect on the task. Was the task easy or hard? Was the task interesting or not? What did you enjoy the most and the least about the task? (3) Did you encounter anything surprising? Confusing? (4) How did your participation help the project meet its science goals? (In other words, how do the citizens' contributions to citizen science actually advance scientific knowledge?)

Outcomes: In order to assess the impact of this assignment on the students, analysis was performed on their logs and final video submissions and using a voluntary pre- and postassignment survey focused on two key questions: (1) does participating in citizen science increase a student's positive attitude toward science, in particular moving from viewing the scientist as "other" toward scientist as "self," and (2) does participating in citizen science increase a students' knowledge of the process of science?

Most student groups were able to accurately describe the scientific goals of their project, to demonstrate the project tasks, and to articulate how they contributed to advancing knowledge. The videos also included rich reflections of the students' experiences, with many comments that indicated they found their work on the projects interesting, such as: “I enjoyed the project as I got to learn about astronomical anomalies, participate in the scientific process, and view pictures many people will never get to see.” Students frequently commented in their logs on the challenge and uncertainty involved in contributing to citizen science, for example: “This was my first attempt at contributing to science, and it was quite a confusing experience.” Fortunately, students tended to become more confident in their contributions after several visits. Students reflected on new insights into the scientific process: “The classification process makes me appreciate the tedious but essential work that helps the science move forward. Not all of it is glamorous and exciting but it is a necessary part of furthering our knowledge of the universe.” Students also expressed a feeling of ownership in their contributions, such as “I feel proud to have contributed to this body of work.”

Changes in students’ attitudes toward science and knowledge of the process of science were uncovered by comparing the results of a brief online survey completed before the introduction of the assignment with the results of the same survey administered again at its conclusion. Preliminary findings indicate that students had a more positive attitude toward science following the assignment, as they were more likely to agree that “participating in science is fun” and less likely to agree with the statement that “participating in science is boring.” Students also showed a slight increase in self-efficacy, as they were less likely to agree that “only a few specially qualified people are capable of understanding science” and more likely to agree that “nearly everyone can understand science (if they work at it).” They were also more likely to agree that they themselves were “capable of learning science” and “making contributions to scientific knowledge.” This aligns well with the fact that interest in contributing to scientific knowledge was the strongest motivator for citizens participating in the Galaxy Zoo Project (Raddick et al. 2010).

8.2.3 Engaging Students in Authentic Research through Citizen Science

The above section provided an example of integrating citizen-science-based assignments into Astro 101 courses with relatively minimal effort, both for the instructors and for the students, and seeing positive student impact. Preliminary results suggest that students both begin to see themselves as capable of contributing to science and gain a more positive attitude toward science. The following example takes this general model of participation in an active online data processing citizen science effort and expands it to include using that experience as the foundation for students to pursue their own research questions with the data the community has generated.

Example: Small Group Research Projects through Citizen Science in Astro 101. Through classroom.zooniverse.org,[5] Astro 101 students engage in a citizen-science-based research experience that is aligned with what scientists actually do, including opportunities to grapple with failure and experience the inherent messiness of science (Szteinberg 2007; Ford & Wargo 2007; Bonney et al. 2009). The project addresses undergraduate students’ lack of experience in aspects of designing investigations that

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[5] Funded by National Science Foundation award #1524189, #1525725, and #1524321.

are important to practicing scientists, including distinguishing between, generating, and manipulating both data and evidence (Lyons 2011); asking scientifically fruitful questions (Karelina & Etkina 2007; Slater et al. 2008); and making predictions, observations, and explanations (Tien et al. 2007; Kastens et al. 2009; Teichert et al. 2017). They engage with their peers in in-depth discussions to collaboratively generate a testable question, carry out data analysis, and draw evidence-based conclusions. Their research experience is divided into distinct milestones, highlighting the practices developed with each step, and revisiting and building on those practices throughout the semester. This approach avoids common pitfalls of active-learning activities in lecture-based courses—confirmatory exercises in which students follow explicit procedures to arrive at predetermined conclusions—and addresses the shortcomings cited in studies in which students show little to no improvement in their understanding of the research process despite the research experience (e.g., Yasar & Baker 2003).

Traditional labs in introductory science courses still generally involve following prescribed steps to reproduce known results, rather than engaging students in experiments that involve authentic scientific practices and the possibility of discovery (Buck et al. 2008; Kloser et al. 2011; PCAST 2012). The National Research Council, the National Academies, and the American Association for the Advancement of Science emphasize that the best way to foster students motivation and interest in science, engage students in performing scientific inquiry, and improve their understanding of the nature of science is through authentic research (National Research Council 1996, 2003, 2010). Embedding authentic research within introductory science courses benefits students in numerous ways. Authentic research experiences not only lead to better understanding of specific course content (Lyons 2011), but have been shown to support students in improving their understanding of the nature of science more generally (Larson-Miller 2011), in asking more scientifically fruitful questions (Karelina & Etkina 2007; Slater et al. 2008), and in making predictions, observations, and developing explanations (Tien et al. 2007). Furthermore, universities face the challenge of serving an increasingly socially, economically, and ethnically diverse undergraduate population, many of whom lack critical preparation for college-level STEM courses. Motivating, engaging, and supporting the learning of all students who enter college science classrooms is an imperative (National Research Council 2003, 2010). Research into the impacts of authentic research experiences on marginalized student groups is limited, but those studies that do exist indicate that these types of experiences can improve retention and outcomes for female students (Kingery 2012), urban students (Chapman 2013), minority students (Gregerman 2008), and special-needs students (Melber 2004).

Curricular design: The classroom.zooniverse.org curricular design and approach was informed by best practices developed through the growing number and network of course-based undergraduate research experiences (CURE[6]). This work also builds on existing efforts in incorporating citizen-science-based research experiences in non-major and major astronomy, geoscience, and biology courses (see the

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[6] https://serc.carleton.edu/curenet/index.html.

"Overview" section, Section 8.1). The design mirrors the Bell et al. (2010) steps in the inquiry process and is informed by the "Science and Engineering Practices outlined in the Next Generation Science Standards." Below we list the assignments we developed for the course within a quarter system (also adapted for and implemented within a semester system). We follow CURE best practices and lessons learned from incorporating citizen science experiences into undergraduate classrooms. These include (1) using quality data and exposing students to how to assess data reliability and validity, (2) a low barrier to technical expertise for data collection, generation, and analysis through a user-friendly interface, (3) a diverse, but constrained, set of variables for developing hypotheses and a data set that lends itself to multiple, unique research questions and multiple pathways for analysis, and (4) course assessments that reflect authentic scientific communication and incorporate peer review.

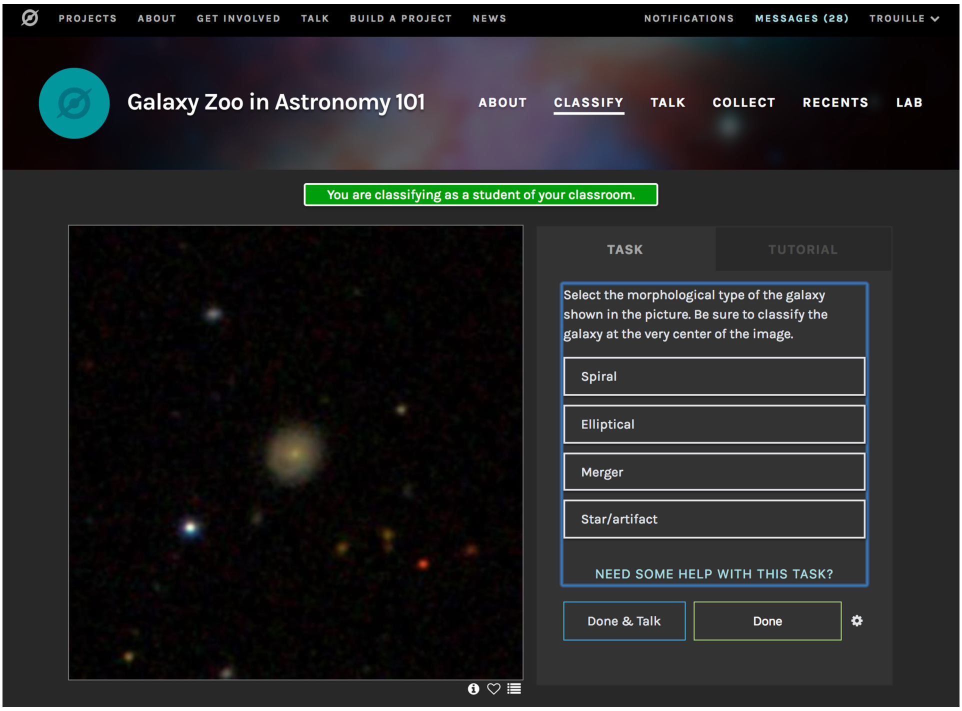
In-class activities: The ~3.5 hours of in-class activities provide the students with a guided use of the platform and data analysis tools they will use in their research projects:

- Introduction: in-class, 30 minute activity during first week of the course introducing citizen science, Zooniverse, and the data analysis platform, guiding students in collecting/inputting data (hometown information, eye color, etc), manipulating the class data, and analyzing the results using the ZooTools data analysis platform.
- Data reliability: before class, students submit 20 classifications to GalaxyZoo.org. (See Figure 8.2 for a screenshot of the Galaxy Zoo landing page.) The in-class, 30 minute activity compares individual, class, and full Zooniverse classification results to expose how multiple classifications for each subject provides a quantitative measurement of the uncertainty and how to use that for data reliability/validity.
- Claims, evidence, and reasoning: two in-class, 60 minute activities using ZooTools to identify and discuss trends in a data set relevant to the core topics typically covered in the first half of the course (e.g., the H–R diagram). Provides scaffolding for using ZooTools as well as for the key plots effort in the research project experience.
- Survey of citizen science opportunities: this 20 minute in-class or out-of-class activity provides exposure to the myriad of in-person and online citizen science opportunities available through major platforms like Zooniverse, Ebird.org, and iNaturalist.org, as well as through the SciStarter.com and CitizenScience.gov repositories with hundreds of projects to participate in.

Research Project Milestones: Students work in small groups over the course of 15–20 hours to carry out their research projects, with opportunities for feedback at each of these milestones.

- Background: near the start of the course, students watch a short "Pinball Process of Science" video and a short video providing additional background on Zooniverse. We also provide links to additional background information and reference materials.

- Introductory activity: student groups carry out a 3 hour mini research experience with the Galaxy Zoo curated data set (Figure 8.2). This curated data set is a random subsample of 25,000 Sloan Digital Sky Survey galaxies in the local universe (specifically a subset of the data used in Masters et al. 2010). We included a limited set of metadata (e.g., mass, redshift, local density, etc.) from Masters et al. (2010) for each galaxy. Groups address the question, "Are all spiral galaxies blue and are all elliptical galaxies red?" (which was the topic of Masters et al. 2010).
- Research question and hypothesis: in their small groups, students discuss, debate, and ultimately agree on which research question they will pursue as a group for their full research experience. To guide them in this process of identifying a valid research question, the students carry out a short, 20 minute activity applying a rubric to assess the validity of research questions.
- Key plots: the groups use our online platform, ZooTools (described below) to analyze the classification results in the context of their research question, including comparing results for the individual, group, class, and full Zooniverse. From these analyses, students identify key plots and statistical analyses that highlight their conclusions best (Figure 8.3).
- Video: the culminating experience is for the students to create short 4 minute videocasts presenting their research question, plots, analysis, and results.



You are classifying as a student of your classroom.

Select the morphological type of the galaxy shown in the picture. Be sure to classify the galaxy at the very center of the image.

Figure 8.2. Screenshot of the Galaxy Zoo interface used in the Astro 101 in-class activity to showcase how online citizen science works and the processes followed to ensure data reliability. Credit: Zooniverse.

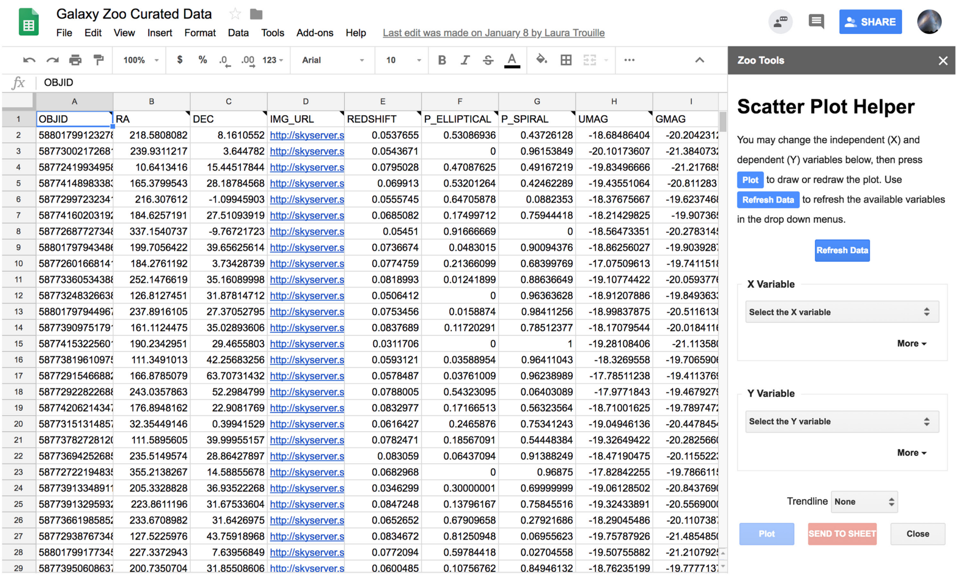
Students use free, easy-to-use software like Screencast-o-matic to simultaneously capture screen and voice recording to create their video. We provide students with a guideline for effective presentations in this format, as well as rubrics for self-assessment, group assessment, and assessment of other groups.

- Peer review: each student provides a peer review for three other videos.

These out-of-class assignments lead the students through the research experience, from classifying galaxies to working in their small research groups to identifying a valid research question, analyzing the data, and communicating their results. This provides students a first-hand experience of the process of authentic scientific research, insight into the true nature of science, and an understanding of basic statistics, essential for a scientifically literate citizen.

All curricular materials and instructional guides are available at https://classroom.zooniverse.org.

ZooTools, the data analysis platform: A major goal of this effort was to make the data analysis aspects of the research experience as accessible as possible to all students, no matter their background in working with data. To this end, we chose to base the classroom.zooniverse.org data analysis tools on Google's Sheets' infrastructure. The Google Suite has been adopted by high schools and universities around the world. In order to make Google spreadsheets even more user-friendly, we created custom, add-on data analysis tools and interfaces to facilitate the students' use of this spreadsheet-based data analysis platform. Our custom Zooniverse add-ons to Google Sheets, hereafter referred to as ZooTools, allow students to more easily apply filters to the full, curated Zooniverse project data set and access basic statistics



	A	B	C	D	E	F	G	H	I
1	OBJID	RA	DEC	IMG_URL	REDSHIFT	P_ELLIPTICAL	P_SPIRAL	UMAG	GMAG
2	5880179912327	218.5808082	8.1610552	http://skyserver.s	0.0537655	0.53086936	0.43726128	-18.68486404	-20.204231
3	5877300217268	239.9311217	3.644782	http://skyserver.s	0.0543671	0	0.96153849	-20.10173607	-21.384073
4	5877241993495	10.6413416	15.44517844	http://skyserver.s	0.0795028	0.47087625	0.49167219	-19.83496666	-21.21768
5	5877414898338	165.3799543	28.18784568	http://skyserver.s	0.069913	0.53201264	0.42462289	-19.43551064	-20.811283
6	5877299723234	216.307612	-1.09945903	http://skyserver.s	0.0555745	0.64705878	0.0882353	-18.37675667	-19.623746
7	5877416020319	184.6257191	27.51093919	http://skyserver.s	0.0685082	0.17499712	0.75944418	-18.21429825	-19.90736
8	5877268772734	337.1540737	-9.76721723	http://skyserver.s	0.05451	0.91666669	0	-18.56473351	-20.278314
9	5880179794348	199.7056422	39.65625614	http://skyserver.s	0.0736674	0.0483015	0.90094376	-18.86256027	-19.903928
10	5877260166814	184.2761192	3.73428739	http://skyserver.s	0.0774759	0.21366099	0.68399769	-17.07509613	-19.741151
11	5877336053438	252.1476619	35.16089998	http://skyserver.s	0.0818993	0.01241899	0.88636649	-19.10774422	-20.059377
12	5877324832663	126.8127451	31.87814712	http://skyserver.s	0.0506412	0	0.96363628	-18.91207886	-19.849363
13	5880179794496	237.8916105	27.37052795	http://skyserver.s	0.0753456	0.0158874	0.98411256	-18.99837875	-20.511613
14	5877390975179	161.1124475	35.02893606	http://skyserver.s	0.0837689	0.11720291	0.78512377	-18.17079544	-20.018411
15	5877415322560	190.2342951	29.4655803	http://skyserver.s	0.0311706	0	1	-19.28108406	-21.11358
16	5877381961097	111.3491013	42.25683256	http://skyserver.s	0.0593121	0.03588954	0.96411043	-18.3269558	-19.706590
17	5877291546688	166.8785079	63.70731432	http://skyserver.s	0.0578487	0.03761009	0.96238989	-17.78511238	-19.411376
18	5877292282268	243.0357863	52.2984799	http://skyserver.s	0.0788005	0.54323095	0.06403089	-17.9771843	-19.467927
19	5877420621434	176.8948162	22.9081769	http://skyserver.s	0.0832977	0.17166513	0.56323564	-18.71001625	-19.789747
20	5877315131485	32.35449146	0.39941529	http://skyserver.s	0.0616427	0.2465876	0.75341243	-19.04946136	-20.447845
21	5877378272812	111.5895605	39.99955157	http://skyserver.s	0.0782471	0.18567091	0.54448384	-19.32649422	-20.282566
22	5877369425268	235.5149574	28.86427897	http://skyserver.s	0.083059	0.06437094	0.91388249	-18.47190475	-20.115522
23	5877272219483	355.2138267	14.58855678	http://skyserver.s	0.0682968	0	0.96875	-17.82842255	-19.786611
24	5877391334891	205.3328828	36.93522268	http://skyserver.s	0.0346299	0.30000001	0.69999999	-19.06128502	-20.843769
25	5877391329593	223.8611196	31.67533604	http://skyserver.s	0.0847248	0.13796167	0.75845516	-19.32433891	-20.556900
26	5877366198585	233.6708982	31.6426975	http://skyserver.s	0.0652652	0.67909658	0.27921686	-18.29045486	-20.110738
27	5877293876734	127.5225976	43.75918968	http://skyserver.s	0.0834672	0.81250948	0.06955623	-19.75787926	-21.485485
28	5880179917734	227.3372943	7.63956849	http://skyserver.s	0.0772094	0.59784418	0.02704558	-19.50755882	-21.210792
29	5877395060863	200.7350704	31.85508606	http://skyserver.s	0.0600485	0.10756762	0.84946132	-18.76235199	-19.777713

Scatter Plot Helper

You may change the independent (X) and dependent (Y) variables below, then press Plot to draw or redraw the plot. Use Refresh Data to refresh the available variables in the drop down menus.

Figure 8.3. Screenshot of the ZooTools interface with the curated Galaxy Zoo data set used in this effort and the scatter plot widget (one of several user-friendly widgets within ZooTools for creating different plot types). Credit: Zooniverse.

(e.g., minimum, maximum, mean, median, standard deviation, etc.). ZooTools also provides a more user-friendly interface for creating plots (e.g., scatter plots, histograms, pie charts, etc.). Figure 8.3 provides a screenshot of the ZooTools interface within Google Sheets. Thus, through classroom.zooniverse.org, the students access our custom ZooTools with a curated Galaxy Zoo data set that includes the classification results and additional metadata of interest (e.g., the galaxy mass, color, distance, environmental density, etc.; values made available via the open data philosophy of the Sloan Digital Sky Survey). We note that the ZooTools code is open source and can easily accommodate data from other major citizen science efforts; we encourage other platforms, e.g., eBird.org, iNaturalist.org, etc., to explore using ZooTools and our curricular framework with their data.

Outcomes: In iteratively developing, assessing, and improving these curricular materials, five instructors at a range of R1, small liberal arts colleges, and community colleges (Northwestern University, University of Minnesota, University of Pittsburgh, University of St. Thomas, and Oakton Community College) supported 725 students in carrying out authentic Galaxy-Zoo-based research experiences through 10 Astro 101 course iterations between 2016 September 1 and 2018 June 15.

T. Nelson et al. (2019, in preparation), to be submitted to the Journal of Geoscience Education, provides an overview of the curriculum, the activities, the feedback from instructors on ease of use and implementation, and the impact on the students. The article presents the results from our pre-/postsurveys and student focus group interviews, including the gains in student understanding of the nature of science and the processes astronomers follow to carry out their research. Student quotes provide illustrations of the survey results, for example, "[Analyzing] the data taught us how easily scientific data can be manipulated and how important it is to know what data set was used and if any data was excluded in reaching a conclusion." We also found significant gains in recognizing the creative nature of research, as illustrated by this quote, "Through conducting this research project, we found that the nature of science has deep roots in creativity."

The article also summarizes the overwhelmingly positive feedback from our pilot instructors and students around ease of implementation (e.g., the clarity of the training and teacher guides, the facility in incorporating these materials into the existing curriculum, their value added, etc.). By implementing at a range of institution types, we have identified how best to adapt these materials to each and created a set of best practices in adapting these core materials to a given institution type, discipline, and course structure. For example, implementation within a community college course must take into account satisfying course credit transfer rules, including upholding existing course objectives and topical requirements.

Because the program includes ~3.5 hours of in-class activities and 15–20 hours for the small group research projects, we explored different models for adapting to quarter and semester systems, lecture versus lab + lecture, and different curricular and institutional constraints. For example, in the Northwestern University Astro 101 lecture course, the research project replaced the 20 hour term paper, worth 20% of the grade, that students had previously submitted. On the other hand, in the

Oakton Community College Astro 101 lecture + lab course, we used three, 3 hour lab periods and 8 hour of out-of-class time (both because this fits better within the course structure and to reduce the required out-of-class group time, which is more of a burden on community college students to accommodate).

The pilot testing also confirmed the astuteness of using Google Sheets + ZooTools—the user-friendliness and simplicity of these tools enabled students' comfort level and ability to carry out the data analysis. This is key for the mostly nonscience majors in these courses to be able to focus on experiencing the processes of science, rather than getting stuck on the data analysis tool itself (a common pitfall for incorporating research experiences into these classrooms).

Sustainability: The Zooniverse team has had good success over the past 10 years of maintaining the Zooniverse.org research projects, infrastructure, and associated curricular materials. Furthermore, we expect Galaxy Zoo to remain active into the foreseeable future, with new data ingested every six months or so. A strength of this effort is that Zooniverse has over 70 active projects; with two to four new projects launching each month (many in astronomy, climate change, and ecology/biodiversity), ZooTools can easily ingest new data sets, and the curricular framework can easily adapt to accommodate new projects in these research areas. We anticipate faculty will create their own Zooniverse projects based around their own research questions and data, and incorporate these projects into this curricular framework and toolkit to use with their students.

8.2.4 Mixing Hands-on Activities with Online Citizen Science

The Planet Hunters Educators Guide[7] is a curriculum developed by Zooniverse educators in conjunction with NASA/JPL introducing students to citizen science and the science behind Zooniverse's popular PlanetHunters.org project. With a heavy emphasis on models to guide student exploration, these lessons were developed to be used independently or to be used as a unit. While the content was originally designed for middle-school classrooms, the materials are relevant and can scale appropriately for Astro 101 courses. Educators have also adapted the Planet Hunters Educators Guide for use in high school, after-school clubs, and informal education settings.

The curriculum begins by introducing students to crowdsourced science by exploring citizen science projects across different platforms including GalaxyZoo.org, the Monarch Larva Monitoring Project,[8] and the GreatSunflower.org. In the second activity, students are introduced to the concept of the "habitable zone" as they identify conditions needed to sustain life on Earth and then determine which other moons and planets in our solar system may also harbor life. Next, students delve into the possibility of life beyond our solar system as they explore known exoplanets and determine if they are within their star's habitable zone. In the third activity, students compare characteristics of different star types and use models to determine habitability zones around these different types of stars.

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[7] https://www.planethunters.org/#/education.

[8] https://monarchlab.org/mlmp.

In activities 4–6, students are introduced to the advantages and disadvantages of different exoplanet detection methods, create models to understand the transit method of exoplanet detection, and begin to analyze light-curve data on Planet Hunters. Through activities 7–9, students become research astronomers as they learn to use light-curve data to assess the habitability of exoplanets. Students begin by creating their own light curves using models to simulate planets transiting a star. They use these data to calculate characteristics of an exoplanet, including how close the planet is to its star and how long it takes to make one trip around the star (i.e., its orbital period). Then, using light curves from Planet Hunters, students are guided through the calculations necessary to determine the orbital period, radius, mass, semimajor axis, density, and surface temperature for their Planet Hunters exoplanet. Finally, just as NASA creates artistic representations of the objects we can indirectly see, students create visualizations of the exoplanets they have been analyzing.

8.3 Astronomical Citizen Science Data Collection Projects

In addition to the above examples of citizen science data analysis and data mining investigations, several astronomy citizen science efforts have engaged students, teachers, and members of the public in the collection of data to help address scientific investigations. In addition to the RECON Project described below, these include but are not limited to Radio JOVE (https://radiojove.gsfc.nasa.gov/), Citizen CATE (https://eclipse2017.nso.edu/citizen-cate/), and SETI CAMS (http://cams.seti.org/).

This type of citizen science research represents another important part of the scientific process, the collection of research data aligned with an investigation. In particular, citizen science data-gathering efforts are highly relevant in cases where data cannot be gathered without a geographically distributed network of collection sites. In cases in which resource and time limitations make it difficult or prohibitive for a small research team to gather data from multiple locations to address a research question, data collection efforts can be conducted by a distributed network of citizen science volunteers who can then provide their data to a central researcher for analysis. Depending upon the scope and requirements associated with accomplishing the research goal, this type of effort can require significant recruitment and coordination efforts. However, distributing data collection responsibilities across a network can allow for otherwise inaccessible research investigations.

8.3.1 Description of the RECON Citizen Science Project

RECON, the Research and Education Collaborative Occultation Network http://tnorecon.net/, is a citizen science astronomy research investigation supported by the National Science Foundation involving over 55 communities stretching across the western United States from Canada to Mexico (Buie & Keller 2016). The research goal of this investigation is to measure the sizes, shapes, moons, rings, and other characteristics of trans-Neptunian Objects (TNOs) down to 100 km in diameter using stellar occultation measurements. A stellar occultation occurs when an object within our solar system (planet, moon, asteroid, etc.) passes in front of a distant star and effectively casts a shadow from that star over Earth's surface. By positioning an array of telescopes in the occultation path and recording the start and end times of the occultation for each location on Earth, researchers can use the known velocity of the solar system object to generate a profile map of the size and shape of the object. This is a commonly used astronomical technique for studying objects throughout our solar system.

The observational challenge faced in the study of outer solar system objects is that the predicted location of the occultation shadow track has a large uncertainty. These uncertainties arise from our estimates of the orbital elements of TNOs. Distant objects like these have orbits extending out beyond Neptune and have only been measured for fractions of their 250+ year orbits around the Sun. This, along with the geometry involved with the alignment of Earth and the distant TNO and even more distant target star, currently results in substantial cross-track uncertainties in the predicted occultation path. The design of RECON was driven by the size of the uncertainty region. By using a large, fixed network, we can relax the required uncertainty for a successful observation. A traditional approach would require uncertainties comparable to the size of the object. RECON is a citizen science approach to deal with this challenge by establishing a picket-fence array of telescopes stretching 2000 km across the US with roughly 50 km spacing. This enhances the probability that at least two of the telescope sites involved will be within the shadow path of a 100 km sized object, resulting in the minimum number of chords required to approximate the size and shape of the occulting body. With the large ground-track coverage, this experiment also covers a much larger area to search for secondary bodies that might be missed by a smaller, more targeted deployment.

In 2008, when the RECON concept was first conceived, establishing such an array of remotely or robotically controlled telescopes was not practical. While the International Occultation Timing Association (IOTA) has a long-standing and well-coordinated network of amateur astronomer citizen scientists, the IOTA community is not distributed densely or regularly enough to accomplish the research goal of systematically measuring 100 km TNOs and searching for binary objects. Thus, the RECON Project has followed the approach of recruiting teachers, students, and community members from roughly 55 targeted communities located between Yuma, Arizona, and Oroville, Washington, to serve as citizen scientists to help in recording occultation data (Figure 8.4). Communities were identified using online geographic software (e.g., Google Maps), and RECON teams were recruited through email, phone, and site visits to local secondary schools and libraries in each community. Telescopes and camera equipment were shipped to participants, and training was provided via three four-day long intensive occultation astronomy workshops for representatives from each team. RECON teams are asked to participate in between six to eight occultation campaigns per year and receive support from the project leadership team throughout the project. Data are recorded electronically and transmitted via the internet to the central data repository, where they are then analyzed by project leadership working with undergraduates.

The RECON Network involves over 50 communities across the western United States. Through support from the NSF, green sites received both telescopes and

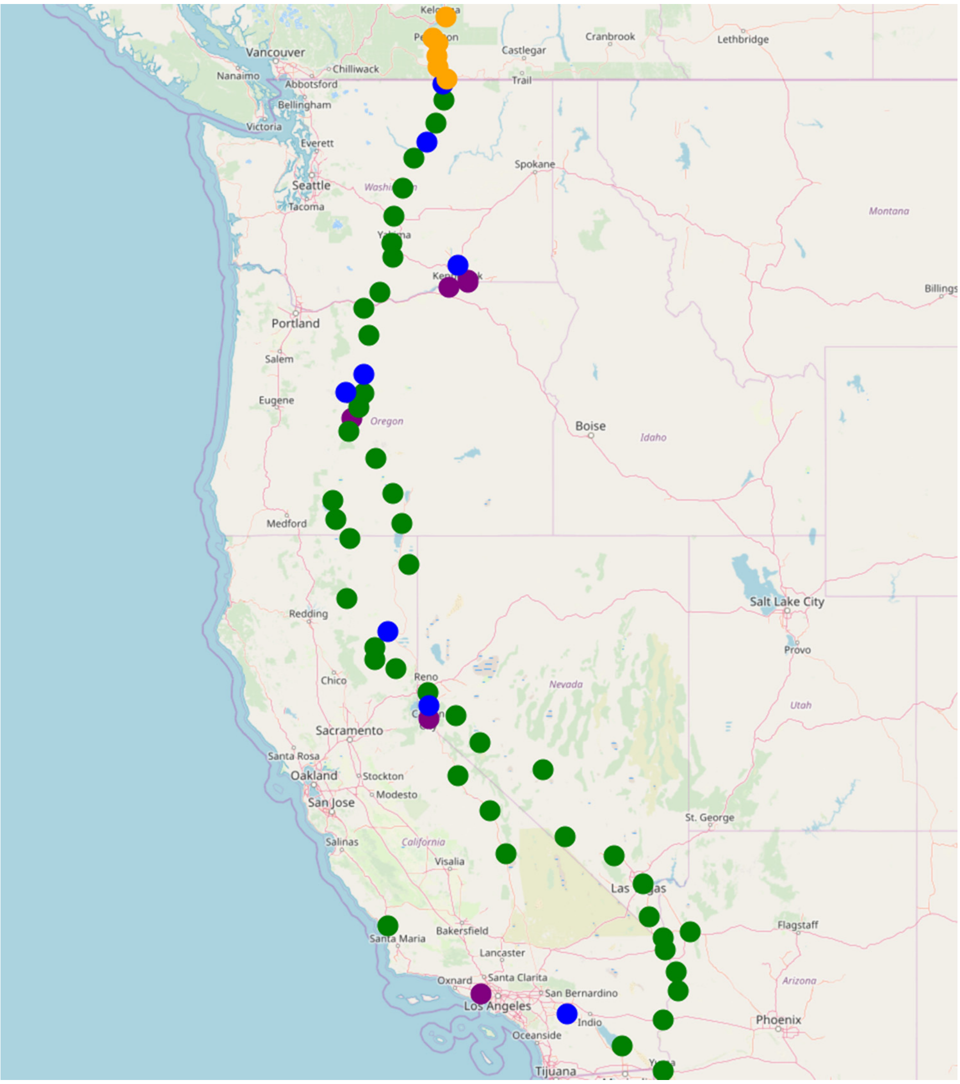

Figure 8.4. A map showing the extent of the RECON telescope network. Note that, in the past year, researchers from the Dominion Astrophysical Observatory have helped to create an international extension of the network, called CanCON, which includes six additional telescope sites north of the border between the U.S. and Canada. Credit: RECON and Map Data © OpenStreetMap contributors.

cameras, blue sites received cameras that were added to existing telescopes, and purple sites contributed their own telescopes and cameras. Recently, yellow sites were added by collaborators in Canada, creating an international extension of the network called CanCON.

The RECON project is an example of a data collection citizen science effort that has engaged over 200 teachers, students, and community members in occultation research. Over the course of the project, an average of 85 adults, 46 K–12 students, and nine college students participate in each full network occultation campaign. The project has successfully measured a Centaur (Buie et al. 2015), a classical Kuiper Belt Object (Benedetti-Rossi et al. 2016), along with additional measurements of Pluto and other TNOs (in preparation).

8.3.2 Citizen Science Insights from the RECON Project

Described below are two significant lessons learned from establishing and maintaining this coordinated research network. First, for RECON, face-to-face interactions were essential to expediting the recruitment process. While email and phone contacts were useful in setting up connections with teachers and community representatives, physical visits to the targeted communities provided a valuable opportunity to emphasize the value of the project to the research community as well as the local community. The concept of stellar occultations was abstract enough that being able to answer questions about the project in person was also a considerable advantage. The leadership team of this project traveled to all of the locations in the network to explain the project and recruit team members.

Second, because many RECON participants did not have prior experience working with telescopes, hands-on training was required. The project team provided three four-day workshops (for the northern, central, and southern regions of the network) to both explain the science of the project and to train team members on the use of RECON telescope and camera equipment. In addition, continued follow-up and individualized support has been important for sustaining project. Since the initial training in the spring of 2015, the project has provided three follow-up science team meetings for representatives from all communities. These team meetings have brought together teachers, students, and community member representatives from each team to provide additional training, share results, and conduct curricular discussions. These meetings have also provided a venue for bringing on new team members over the course of the project. This has been particularly useful given that the project has experienced an annual teacher attrition rate of 5%–10% since initial training events.

The above insights are generalizable to other citizen science efforts in which specific geographical sites are required to accomplish the scientific investigation. For example, the Citizen CATE project required locating telescopes along the midline of the path of totality for the 2017 solar eclipse. There are many citizen science data collection efforts in which the specific location of the data collection site is not predetermined and researchers can rely on a random distribution of volunteers to collect useable data (e.g., Project BudBurst, https://budburst.org/, Radio JOVE, https://radiojove.gsfc.nasa.gov/).

Through citizen science research efforts, participants are engaged in many science and engineering practices (NGSS Framework). With both Zooniverse and RECON, participants are involved in, among other practices, planning and carrying out investigations; analyzing and interpreting data; developing and using models; and obtaining, evaluating, and communicating information. Project participants also engage in troubleshooting and engineering practices of defining problems and designing solutions. While the RECON project leadership was initially responsible for identifying the central research question and planning the coordinated network to observe TNOs, citizen science team members have contributed to refining and improving the research effort throughout the project. There are other community-based citizen science efforts in which students and community members play even larger roles in asking initial research questions and planning full research investigations about local community issues. For example, in the East Bay Academy for Young Scientists (http://static.lawrencehallofscience.org/ays/), with support from the Lawrence Hall of Science, K–12 students identify local environmental and societal issues, fully develop research investigations, and present results of findings at research conferences, thereby participating deeply in the full process of scientific investigation. Through citizen science, participants grow in their understanding, skills, and identities as researchers contributing to our scientific understanding of the world.

8.4 Summary

Citizen science has proven to be a powerful research tool, enabling researchers to solve problems involving large quantities of data (e.g., Carvajal et al. 2018), discover rare or unusual objects (e.g., Boyajian et al. 2016), have important impacts on environmental and social justice issues (e.g., Theobald et al. 2015), and more. In parallel to the rise in quality and impactful citizen science projects over the past decade, there has been an explosion in opportunities to incorporate citizen science into formal and informal education. Citizen science provides instructors an opportunity to engage students in the process of scientific discovery while making real and valued scientific contributions in ways that are well aligned with research-supported educational practices.

Our goal for this chapter was not to provide an exhaustive listing of citizen science uses in astronomy classrooms, but rather to focus on a few examples in order to highlight best practices and guiding principles. Many of these principles mirror those developed through the CURE efforts, including (1) using quality data and exposing students to how to assess data reliability and validity, (2) a low barrier to technical expertise for data collection, generation, and analysis through a user-friendly interface, (3) a diverse, but constrained, set of variables for developing hypotheses and a data set that lends itself to multiple, unique research questions and multiple pathways for analysis, and (4) course assessments that reflect authentic scientific communication and incorporate peer review.

In order to showcase some of the diversity in citizen science opportunities, we highlighted examples from two distinct platforms and approaches: (1) the Zooniverse platform for online citizen science and (2) the RECON coordinated telescope observing and research network. Within the Zooniverse context, we shared two models for student engagement. In Section 8.2.2, we described the impact of students contributing regularly to one of the Zooniverse astronomy-based projects over the course of a month and reflecting on that experience. This is an approach that takes minimal effort on both the instructor and students but has real impact on student attitudes. In Section 8.2.3, we build on this base model and add a more in-depth research component to the experience (using a curated Galaxy Zoo data set), as well as exposure to the full Zooniverse ecosystem of projects across the disciplines and of the broader ecosystem of citizen science opportunities listed through citizenscience.gov and SciStarter.org. In Section 8.2.4, we provided an example of extending hands-on classroom experiences with online citizen science. In Section 8.3.1, we provided an overview of RECON, an astronomy research investigation involving a coordinated network of citizen science observers. Highlighted in Section 8.3.2 were the importance of personalizing the interaction between researchers and volunteers and providing training and support for participants. Depending upon the project, these goals can be accomplished online but can also benefit from in-person interaction.

We hope these examples serve as a useful starting point and inspiration for instructors looking to incorporate citizen science into their classrooms.

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