Ideas for Citizen Science in Astronomy

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Abstract

We review the relatively new, internet-enabled, and rapidly-evolving field of citizen science, focusing on research projects in stellar, extragalactic and solar system astronomy that have benefited from the participation of members of the public, often in large numbers. We find these volunteers making contributions to astronomy in a variety of ways: making and analyzing new observations, visually classifying features in images and light curves, exploring models constrained by astronomical datasets, and initiating new scientific enquiries. The most productive

citizen astronomy projects involve close collaboration between the professionals and amateurs involved, and occupy scientific niches not easily filled by great observatories or machine learning methods: citizen astronomers are most strongly motivated by being of service to science. In the coming years we expect participation and productivity in citizen astronomy to increase, as survey datasets get larger and citizen science platforms become more efficient. Opportunities include engaging the public in ever more advanced analyses, and facilitating citizen-led enquiry by designing professional user interfaces and analysis tools with citizens in mind.

CONTENTS

1 INTRODUCTION

The term "citizen science" refers to the activities of people who are not paid to carry out scientific research ("citizens"), but who make intellectual contributions to scientific research nonetheless.[1] They come from all walks of life, and their contributions are diverse, both in type and research area. This review is about the astronomy projects they have participated in to date, the tasks they have performed, and how astronomy has benefited – and could benefit further – from their efforts.

Citizen involvement in science pre-dates the profession itself. The earliest example of collaboration between professional and amateur astronomers seems to have been Edmund Halley's call for observations of the 1715 total eclipse of the Sun which crossed central England (Halley 1716).[2] Since then there has been

[1]In this review we differentiate between the data analysis that citizens carry out themselves, and distributed "grid" computing farmed out to processors owned by citizens, and omit the latter since it does not fit our definition of citizen science as involving intellectual contributions from citizens.

[2]The aim was to refine estimates of the size of the shadow cast by the Moon, and citizen observations were much needed. Although Halley was successful in observing, his colleagues at Oxford were clouded out, and those in Cambridge were "oppressed by too much Company, so that, though the heavens were very favourable, [they] missed both the time of the beginning of the Eclipse and that of total darkness."

a long and honourable tradition of amateur observers making important discoveries and significant sustained contributions. However, the advent of the world wide web has changed the face of professional and amateur collaboration, providing new opportunities and accelerating the sharing of information. People are now connected to each other on a scale that has never happened before. Professional scientists can interact with citizens via a range of web-based media, including purpose-built citizen science websites which increase the potential for shared data analysis and exploration, as well as for data collection. Meanwhile, communities of citizens have sprung into existence as like-minded people have been able to find and talk to each other in a way that is almost independent of their geographical location. The result has been an exponential increase in citizen involvement in science. The field is evolving very quickly, with more and more professional scientists becoming aware of the possibilities offered by collaborating with, for example, specialists operating outside the usual parameters of professional astronomical observation, or tens of thousands of people eager to perform microtasks in their spare time.

Our aim in this work is to review the astronomical (and occasionally wider) literature for productive citizen science projects, and distill the characteristics that made these case studies successful. As our title states, this is a review of ideas for astronomy: we will look forward as well as back, and try to answer the following questions. What are the particular niches that citizen science fills, in our field? What is the potential of citizen science in astronomy, and how can it be realized?

This review is organised as follows. Astronomy research typically starts with observations: so do we, in Section 2. We then proceed to consider visual classifi-

cation, data modeling and finally citizen-led enquiry in Sections 3–5. With this overview in place, we take a look in Section 6 at the population of citizens who take part in astronomical research. We then turn to the future, and speculate on how citizens might contribute to astronomy there (Section 7), and finish with some concluding remarks in Section 8.

2 AMATEUR OBSERVING

There is currently an active community of well-equipped amateur observers making astronomical observations of great utility. There are also many other citizens observing the night sky with less sophisticated equipment – and as we shall see, there are even some examples of citizens making astronomical observations almost inadvertently. What astronomical data are the citizenry taking, and what is it being used for?

2.1 Active Observing

In this section, we review some of the citizen contributions to active observations of the night sky. "Passive" contributions will be described in Section 2.2 below. The steady improvements and increasing affordability of digital technology, in addition to the ease of data sharing and communications, have considerably expanded the realm of amateur astronomy in the past two decades. Meanwhile, professional observatories are always over-subscribed, with resources necessarily being divided between particular areas of sky, or samples of objects, or on a few astronomical questions: tuning the parameters of professional observations to optimize all possible scientific enquiries would seem an impossible task. What types of niches does this leave for amateur observers to fill? What are the strengths

that amateur observers can play to?

The first key advantage that amateurs have is time availability. Determinations of meteor frequencies (for example) require observations on short timescales (minutes), whereas the slow evolution of giant planets (for example) occurs on longer timescales (years and decades). Amateur observations can be frequent and repetitive, but also long standing.

The second, related, advantage is that of flexibility: whenever a new phenomenon is discovered (e.g., a new comet, or anything changing the appearance of the familiar planetary discs), observers will be keen to catch a glimpse irrespective of the scientific value of their observations. This reaction can be near instantaneous, compared to the need to allocate telescope resources among the professional community, and, when made by a networked community, provides naturally well-sampled coverage across the globe.

The third benefit is contextual. Professional observations are often taken in a very different wavelength range, focus on a narrower spatial region, or employ spectroscopic techniques that don't yield images. In some situations, near-simultaneous wide field optical imaging by citizen scientists can provide useful additional constraints on the process of interest.

The example case studies below serve to illustrate this synergy between amateur and professional observations, and also to highlight instances of professional-amateur ("Pro-Am") collaboration. While the solar system provides some of the most amenable targets for amateur observation, "deep sky" observations by the non-professional community provide important further insight into the capabilities and potential of citizen astronomers.

Discovery and characterisation of asteroids and comets. Although

survey telescopes provide the vast majority of modern solar system discoveries, citizen astronomers occupy some useful observational niches. Small solar system objects moving against the fixed-star background can be detected in a set of CCD frames either by eye or by automated software. Targets include near-earth asteroids (NEAs, with orbits intersecting those of the terrestrial planets), main belt asteroids between Mars and Jupiter, and comets making their journey towards the Sun from the outer solar system. The extreme familiarity of citizen astronomers with a particular region of sky, planet or nebula, allows them to immediately identify peculiarities or new features. A protocol for citizen discovery has been established: the position of any new object is compared to existing catalogues, and if no existing details are found then the new discovery and its ephemerides can be reported to the IAU Minor Planet Center.[3] If observations are repeated for at least two nights by one or several observers, then a new denomination is provisionally assigned to the discovery. An electronic circular then reports the discovery to the wider world. For example, the NEA 2012 DA14 was initially reported to the Minor Planet Center by a team of amateur observers affiliated with the La Sagra Sky Survey at the Astronomical Observatory (Spain), and subsequently characterised by professional astronomers during its closest approach in February 2013 (e.g., de León et al. 2013).

As with asteroids, the majority of new comet discoveries are made by automated surveys, but a small and stable number of discoveries come from amateurs with small telescopes, typically in regions poorly covered by survey telescopes (e.g., regions close to the Sun). C/2011 W3 (Lovejoy), a Kreutz sungrazer comet, is one such example, discovered by T. Lovejoy and circulated via the

[3] `http://www.minorplanetcenter.net`

Central Bureau for Astronomical Telegrams (CBAT) (e.g., Sekanina & Chodas 2012). The Oort cloud comet C/2012 S1 (ISON) was spotted by V. Nevski and A. Novichonok in images from the International Scientific Optical Network, which spurred a major international effort to observe its perihelion passage as it disintegrated (Sekanina & Kracht 2014). Amateurs are also contributing to the search for a sub-category of objects with a detectable cometary coma within the asteroid belt. Recent discoveries of these main belt comets, which appear to be asteroids that are actively venting their volatiles at perihelion, are beginning to blur the distinction between asteroids and comets. The T3 project, a collaboration between the University of Rome and several amateur observers, began in 2005 with the detection of a coma around asteroid 2005 SB216 (Buzzi et al. 2006), and has gone on to detect at least eight main belt comets (Mousis et al. 2014). These early citizen science discoveries, followed up by professional astronomers, have generated new insights into the properties and variety of comets, and the dynamic and evolving nature of our solar system. The discovery of Comet Shoemaker-Levy 9 (co-discovered by amateur observer D. Levy) before its collision with Jupiter (Harrington et al. 2004) is a classic example. In general, it is the global distribution of citizen observers and the long-baselines of their observations that enable new discoveries of minor bodies in our solar system.

Beyond first detections, citizen observers can aid in the detailed study of the physical and orbital characteristics of these newly discovered solar system bodies. These amateur-led contributions are typically published via the *Minor Planet Bulletin*.[4] Photometric monitoring of an asteroid as it rotates provides information on its physical parameters such as its shape, rotation rate and orientation;

[4] `http://www.minorplanet.info/mpbdownloads.html`

monitoring of a comet's coma, dust and plasma tails can reveal dynamic structures, determine the locations of active venting regions and reveal outbursts and other events associated with the outgassing (see Mousis et al. 2014, for a comprehensive review).

Planetary monitoring over long timescales Planetary atmospheres make tantalising targets for citizen observers, being large, bright, colourful and highly variable from night to night (e.g., Figure 1. The long-term monitoring provided by the network of amateur astronomers provides valuable insights into the meteorology and climate of these worlds, tracking the motions of clouds, waves and storms as they are transported by atmospheric winds to probe the physical and chemical processes shaping their climates. For example, the global distribution of giant planet observers permits global monitoring of Jupiter and Saturn as they rotate over 10 hours. Citizens upload raw filtered images and colour composites, organised by date and time, to online servers, such as the Planetary Virtual Observatory and Laboratory (PVOL[5]) maintained for the International Outer Planets Watch (IOPW Hueso et al. 2010). Those images can be used by amateurs and professionals alike to study quantitatively the visible activity, including measuring wind speeds from erupting plumes (Sánchez-Lavega et al. 2008), investigating the strength and changes to the large vortices (e.g., the 2006 reddening of Jupiter's Oval BA, Simon-Miller et al. 2006), and determining the life cycle of the belt/zone structure (Fletcher et al. 2011, Sánchez-Lavega et al. 1996). For Saturn, a close collaboration between citizen scientists and Cassini spacecraft scientists (known as Saturn Storm Watch) has allowed correlation of lightning-related radio emissions detected by the spacecraft with visible cloud

[5] `http://www.pvol.ehu.es/pvol`

structures on the disc (e.g., Fischer et al. 2011), which would not have been possible with the targeted regional views provided by Cassini's cameras alone. Furthermore, it was the amateur community that first spotted the eruption of Saturn's enormous 2010-2011 storm system, which was monitored over several months (Sánchez-Lavega et al. 2012).

Video monitoring has been used by citizen observers to enable high resolution "lucky" imaging of Jupiter. The best images, at moments of clear seeing, from the high-resolution video frames are selected, extracted and stacked together, using custom software to correct for the distortions associated with the telescope optics and residual atmospheric seeing. Software written by citizen scientists for free distribution to active observers, such as Registax[6] and Autostakkert[7], allows them to process their own video files, thus avoiding the need for transfer of large datasets to some centralised server (see Mousis et al. 2014, for a thorough review). Descriptive records of morphological changes are maintained and continuously updated by organisations of citizen scientists such as the British Astronomical Association (BAA) and the Association of Lunar and Planetary Observers (ALPO). The BAA's Jupiter section[8] is a team of amateurs with substantial expertise in Jupiter's appearance (Rogers 1995); their regular bulletins describe the changing appearance of the banded structure and the emergence of new turbulent structures and weather phenomena, and keep a record of the long-term atmospheric changes.

Active citizen observing also provides long-term monitoring in the inner solar system. Venus' photochemical smog shields the planet's surface from view, but

[6] www.astronomie.be/registax

[7] www.autostakkert.com

[8] `http://www.britastro.org/jupiter`

discrete cloud features can be used to study the super-rotation of the Venusian atmosphere, and the occurrence of a mysterious ultraviolet absorber at high altitudes. For example, the Venus Ground-Based Image Active Archive was created by ESA to provide contextual observations supporting the Venus Express mission (Barentsen & Koschny 2008). The Martian atmosphere, with its ephemeral clouds, seasonal CO_2 polar ice cycles, and dust storms, continues to prove popular among citizen observers, although these are a minor supplement to the wealth of high-resolution information being returned by orbital and surface missions to the red planet. As with other planetary targets, amateur observations provide the long temporal records of the evolution of atmospheric features. Groups such as the International Society of Mars Observers (ISMO[9]), the British Astronomical Association (BAA) and the International Mars Watch program quantitatively and qualitatively assess these amateur images. Finally, although citizen observations of Uranus and Neptune are in their infancy and require telescopes with diameters exceeding 25 cm, there have been confirmed reports of atmospheric banding and discrete cloud features when near-infrared filters (to maximise the contrast between the white clouds and the dark background) and long exposure times of tens of minutes are used. Citizen monitoring of all of these worlds (summarised in Figure 1) provides the long-baselines, flexibility and high frequency of imaging needed to understand the forces shaping their evolving climates.

Solar System Impacts. The increasing adoption of video monitoring of planetary targets means that unexpected, short-lived events on the surfaces of those bodies are now more likely to be observed by citizen astronomers than by professional observatories. For example, an impact scar near Jupiter's south po-

[9] `http://www.mars.dti.ne.jp/ cmo/ISMO.html`

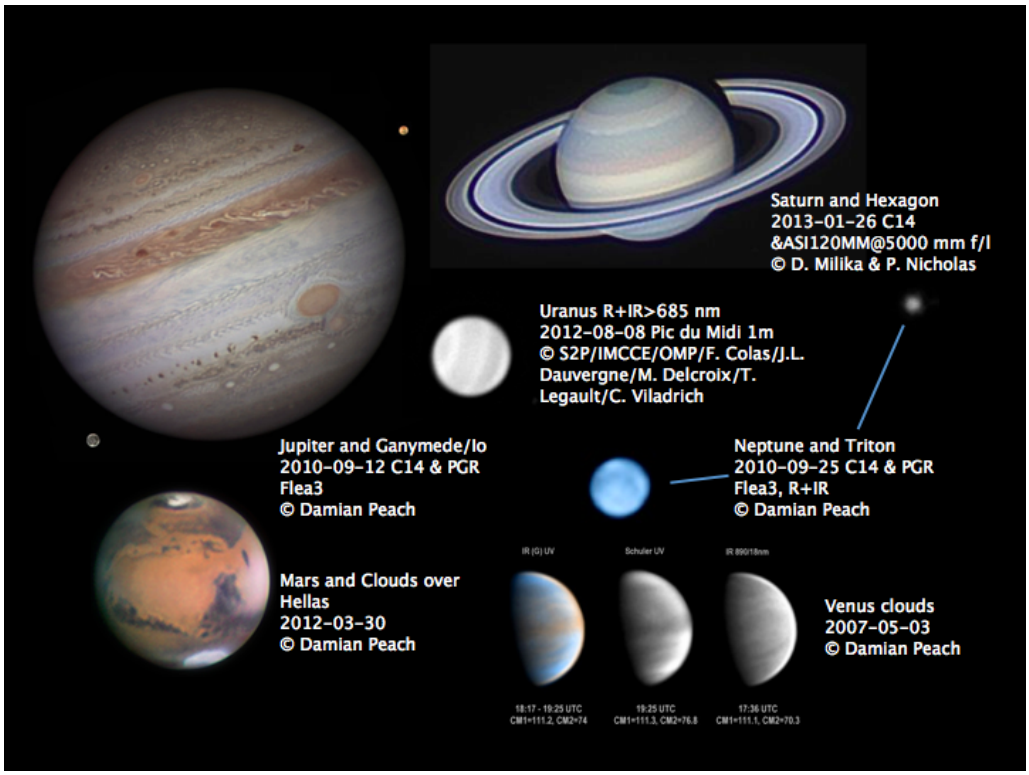

Figure 1: Examples of high fidelity images obtained by amateur planet observers.

lar region was first discovered in imaging by Australian amateur Anthony Wesley on July 19th, 2009. This led to an international campaign of professional observations to understand the asteroidal collision that had created the scar (e.g., de Pater et al. 2010, Hammel et al. 2010, Orton et al. 2011). Although the 2009 impact was out of view from the Earth, at least three flashes have been confirmed between 2010 and 2012, and the light curves used to determine the sizes and frequency of objects colliding with Jupiter (e.g., Hueso et al. 2010) (Figure 2). Citizen scientists have developed free software to allow observers to search for impact flashes in an automated way (e.g., Jupiter impact detections[10] and LunarScan from the ALPO Lunar Meteoritic Impact Search for transient

[10] `http://www.pvol.ehu.es/software`

impact flashes recorded on the moon [11]).

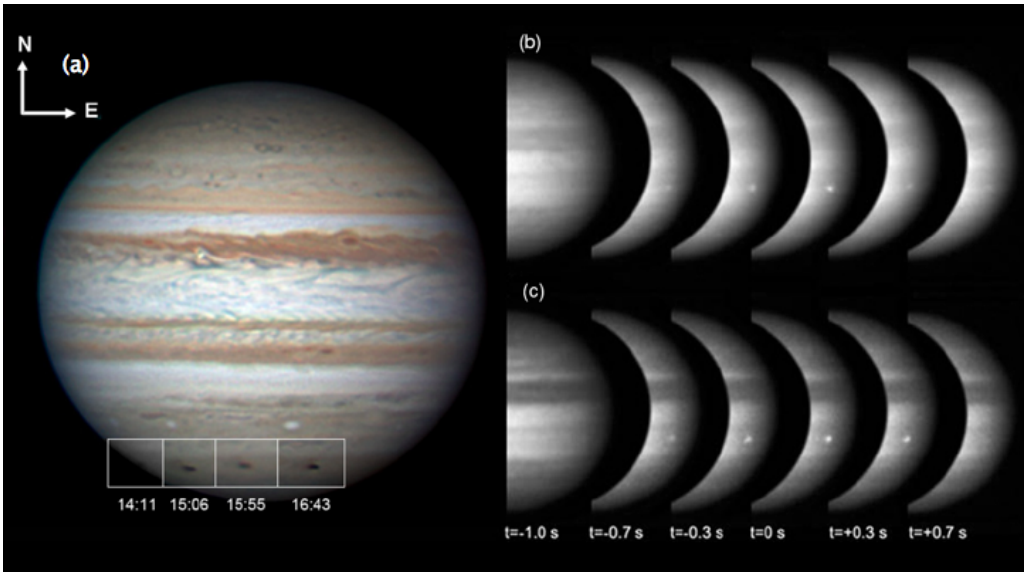

Figure 2: Citizen science contributions to monitoring of impacts in the Jupiter system. (a) Dark impact scar in Jupiter's atmosphere imaged by Anthony Wesley on July 19th 2009 (Sánchez-Lavega et al. 2010). (b) The evolution of a smaller bolide impact on June 3rd 2010 at red wavelengths, also imaged by Wesley. (c) The evolution at blue wavelengths by Christopher Go, figure from Hueso et al. (2010).

Transiting and Microlensing Exoplanets. Amateur observers have contributed to several exoplanet investigations, responding to detections made by professional surveys and making important contributions to the light curves of the targets. In the case of exoplanet transits, the challenge is to measure the 1% diminution in starlight as a giant planet transits in front of its parent star. Mousis et al. (2014) point out three methods whereby amateurs can contribute to the characterisation of exoplanetary systems: first, by frequent observations of known transits to refine ephemeris; second, by searching for transit time vari-

[11] `http://alpo-astronomy.org/lunarupload/lunimpacts.htm`

ations that can reveal additional planets in a system; and third, by searching for previously unidentified transits in known planetary systems (e.g., the discovery of the transit of HD 80606b from a 30 cm telescope near London, Fossey, Waldmann & Kipping 2009). In a planetary microlensing event, significant brightening of the background star is required to make a planet orbiting the microlens visible at all; if additional caustic crossings are caused, the resulting exoplanetary microlensing feature is of just several days duration, calling for high frequency, on demand monitoring – a situation well matched to the capability of a global network of small telescope observers (see e.g. Christie 2006). High magnification events detected by the OGLE[12] and MOA[13] surveys have been broadcast by the microFUN[14] and PLANET[15] networks (now merged) to globally-distributed professional and amateur observers to follow up. These collaborations have been very successful, helping enable characterisation of over a dozen exoplanet systems (see e.g. Gould et al. 2014, Udalski et al. 2005, and references therein).

Variable Star Monitoring: the AAVSO. The American Association of Variable Star Observers (AAVSO) supports and coordinates the efforts of over 900 amateur observers who are interested in bright, nearby variable stars; in 2013, the community made over a million observations, either visually or with CCD or DSLR cameras, and logged them into a shared database.[16] The AAVSO provides a number of services to assist the volunteers, including training material, an online data entry tool that carries out basic error checking, several pieces of software to assist the observers in checking their own observations, and data

[12] `http://ogle.astrouw.edu.pl/`

[13] `http://www.phys.canterbury.ac.nz/moa`

[14] `http://www.astronomy.ohio-state.edu/ microfun`

[15] `http://planet.iap.fr`

[16] The AAVSO annual reports can be found at `http://www.aavso.org/annual-report`

reviews by AAVSO staff. Despite its name, AAVSO observers are located all over the world, with two thirds of the membership working outside the US. Some of the community's larger telescopes can be operated robotically, and have been linked together into a network, AAVSOnet. This network is engaged in an ongoing all sky survey, APASS,[17] which is carrying out a survey of over 50 million stars between 10th and 17th magnitude, in 5 optical filters ($BVg'r'i'$). The data processing and calibration is being done as a Pro-Am collaboration, and the data is being released at approximately annual intervals.

The distributed nature of the AAVSO community means that it can produce continuous light curves for stars at a wide range of declinations. The AAVSO data has been used extensively by professional astronomers needing the most up to date optical measurements of stellar variability in, for example, the SS Cyg system (Miller-Jones et al. 2013), optical light curves taken simultaneously with monitoring being carried out by space telescopes and/or at different wavelengths (see *e.g.* Szkody et al. 2013, for a successful joint AAVSO–HST program), or who are performing long baseline data mining analyses of variable star populations.

The AAVSO, in partnership with several professional astronomers and education specialists, successfully coordinated the NSF-funded "citizen sky" project to monitor the 2009–2011 eclipse in the espilon Aurigae binary star system. The results from this campaign (Stencel 2012)[18] were used by Kloppenborg et al. (2010) to help interpret their interferometric imaging of the obscuring disk in the system.

[17] `http://www.aavso.org/apass`

[18] The results from the Citizen Sky project are presented in a special issue of the JAAVSO at `http://www.aavso.org/jaavso-v40n2`

2.2 Passive Observing

While amateur astronomers have aquired a great deal of very useful data, the general population is better equipped than ever to image the sky and make that data available for scientific analysis. This has been demonstrated by two recent professionally-led studies, that made use of a largely passive observing community connected via online social networks not usually associated with astronomy.

The Orbit of Comet Holmes from the Photographs Uploaded to Flickr. Lang & Hogg (2012) used more than 2000 images scraped from the photo sharing website Flickr as inputs to a reconstruction of the orbit of Comet Holmes. This comet was bright enough to be visible with the naked eye during its 2007 apparition, and a large number of photographs were taken of it and uploaded to the Flickr site. Lang & Hogg were able to astrometrically calibrate many of the images using their automatic image registration software, `astrometry.net` (Lang et al. 2010), which detects the stars in each image and matches them to those in professionally-assembled catalogs. This had been enabled as a Flickr "bot," crawling over all images submitted to the `astrometry.net` group[19] and sending the photos' owners messages showing them where on the sky their images were taken. The time of observation could in many cases be derived from metadata included in the image headers. The calibrated images trace out the trajectory of the comet, producing a result which is close to that obtained from the JPL Horizons system (Giorgini et al. 1997). Estimates of orbital parameters from Flickr images alone are accurate, when compared to the Horizons values, to within a few standard deviations. As the authors point out, while in this case the photographers did not realize they were participating in a scientific study,

[19] `https://www.flickr.com/groups/astrometry`

the potential of combining powerful calibration software with large amounts of citizen-supplied imaging data is made clear. This method of "unconscious" citizen science may prove to have significant value in fields beyond astronomy too, if models of the statistical sampling can be developed, with ecological surveys of images submitted to sites like Flickr likely in the next few years.

Informal Earth-Meteor Impact Detection. As well as observing other planets for impacts, citizen scientists have also played a crucial role in the recording of asteroid impacts on Earth, although not always realizing the usefulness of their observations. Video footage of the fireball and shockwave of the February 2013 Chelyabinsk meteor (Popova et al. 2013) were essential to scientifically characterise the impactor and its likely origins, despite the fact that these records were largely captured accidentally by autonomous security cameras. Trajectories reconstructed from these records even permitted the recovery of meteorites from a debris field on the ground.

Such objects are fragments of comets and asteroids, the debris left over from the epoch of planetary formation: their numbers, sizes and composition provide a window into the earliest evolutionary stages of our solar system. The statistics of these impacts reveal the risk of threats in our local neighbourhood, and these statistics are currently actively provided via a global network of citizen scientists, sharing and publicising their observations of meteors via the International Meteor Organisation (IMO[20]). However, visual observations of meteors can also be tracked with no such active participation. By searching the archive of short text messages submitted to the web service Twitter, Barentsen et al (priv. comm.) were able to detect several new meteor showers. Naked-eye observers had spot-

[20] `http://www.imo.net`

ted shooting stars and tweeted about them to their followers, giving rise to a detectable signal in the steam of tweets that night.

3 VISUAL CLASSIFICATION

Observing the night sky with a telescope is perhaps the most familiar of the activities of amateur astronomers, but as the previous section showed, citizens are also actively involved in the processing and interpretation of the data they have taken. In this and the next section we look at projects where much larger archival astronomical datasets have been made available to crowds of citizens, who are asked to inspect images and light curves, and help describe and characterize the features in them. Despite significant advances in machine learning and computer vision, the visual inspection of data remains an important part of astronomy, as it continues to take advantage of the amazing human capacity for visual pattern recognition. While many in the 1990s predicted that the increasing size of astronomical datasets would make such time-intensive inspection impossible, the extensive reach of the world wide web has enabled the involvement of hundreds of thousands of citizen scientists in this form of "crowd-sourced" data analysis.

3.1 Crowd-sourced Classification in Astronomy

Stardust@home While significant preliminary work had been carried out by NASA's "clickworkers" (see below), the project that first illustrated the potential of crowd-sourcing for astronomical purposes was Stardust@home[21]. The team asked volunteers to scan through images of samples returned from Comet Wild-2 by the Stardust mission, attracted a large audience to the apparently

[21] `http://stardustathome.ssl.berkeley.edu/`

unprepossessing task of looking for dust grains in an effort to identify samples of material from outside our Solar System. The site was built on BOSSA, an early attempt to build a generalized platform for such crowd-sourcing projects, and featured a stringent test which volunteers had to pass before their classifications would be counted. Despite this hurdle, more than 20,000 people took part, and a variety of dust grains were removed from the aerogel for further study, contributing two of the seven candidate interstellar grains presented in a recent Science paper(Westphal et al. 2014). Perhaps the most significant long-term impact of Stardust@home, though, was the demonstration that large amounts of volunteer effort were available even for such seemingly uninspiring tasks such as hunting dust grains in images unlikely to be described as intrinsically beautiful, and that, with a suitable website design and stringent testing, scientifically valuable results could be obtained.

Galaxy morphology with Galaxy Zoo

The Stardust@home experience directly inspired the development of Galaxy Zoo, perhaps the most prominent scientific crowd-sourcing project to date. Galaxy Zoo was built on the continued importance of morphological classification of galaxies, first introduced in a systematic fashion by Hubble, and later developed by, among others, de Vaucoleurs. While the morphology of a galaxy is closely related to its other properties, such as colour, star formation history, dynamics, concentration and so on, it is not entirely defined by then: there is more information in resolved images of galaxies than is captured in these observables. One approach was to develop simple proxies (e.g CAS (Conselice 2006)), but these are at best approximations for true morphology.

In an effort to prepare for large surveys, such as the Sloan Digital Sky Survey

(SDSS), Lahav et al. (1995,1996), and later, Ball et al. (2004) developed neural networks trained on small samples of expert classified images,[22] in order to automate the process of classification arguing that the size of the then up-coming surveys left no place for visual classification.

The performance of these automatic classifiers depended on the input parameters, including colour, magnitude and size. These variables correlate well with morphology, but are not themselves morphological, and when included they dominate the classification. In particular, for galaxies which do not fit the general trends, such as spirals with dominant bulges, or star-forming ellipticals, automated classifiers, whether using these simple measures or more complex proxies for morphology such as texture, fail to match the performance of expert classifiersLintott et al. (2008). As a result, Schawinski et al. (2007), Nair & Abraham (2010), and others have spent substantial amounts of time visually classifying tens of thousands of galaxies.

Inspired by Stardust@home, a small group led by one of the authors (Lintott) created Galaxy Zoo in 2007 to provide basic classifications of SDSS galaxies[23] Classifiers were presented with a coloured image centered on and scaled to one of more than 800,000 galaxies, and could select from one of six options to characterise that object's morphology: clockwise, anti clockwise and edge-on spirals, ellipticals, mergers and "star/don't know." Aside from an easily-passed initial test, little knowledge was required or indeed presented to classifiers, enabling them to proceed quickly to doing something real soon after arriving at the site;

[22]The Lahav papers are perhaps as interesting for their psychology as for their astrophysics, as the classifications reveal the relations between the senior classifiers employed to be experts.

[23]The original Galaxy Zoo is preserved at `http://zoo1.galaxyzoo.org` with the current incarnation at `http://www.galaxyzoo.org`.

this approach, in contrast to Stardust@home, was successful in encouraging large numbers of visitors to participate. This tactic – in which both passing and sustained engagement provide substantial contribution – is illustrated in Figure **??** which shows results from Galaxy Zoo 2. This later version of the project asked for more detailed classifications via a decision tree containing questions such as 'How prominent is the bulge?', and later iterations of the project have applied a similar approach to galaxies drawn from Hubble Space Telescope surveys including GEMS, GOODS, COSMOS and CANDELS.

Figure 3: Distribution of effort amongst 5000 randomly selected volunteers from Galaxy Zoo 2. The area of each square represents the classifications of a single user; colours are randomly assigned. The diagram illustrates the importance of designing for both committed and new volunteers as both contribute significantly.

To date, several hundred thousand people have participated in the Galaxy Zoo project, but such figures would be meaningless if the classifications provided were not suitable for science. With sufficient effort to ensure each galaxy is classified multiple times (as many as 80 for many Galaxy Zoo images), these independent classifications need to be combined into a consensus. As discussed in later sections, this can become complex, but for Galaxy Zoo a simple weighting which rewards consistency, first described in Land et al. (2008), was deemed sufficient. Importantly, combining classifications provides not only the assignment of a label but, in the vote fraction in a particular category, an indication of the reliability of the classification. This allows more subtle biases, such as the propensity for small, faint or distant galaxies to appear as elliptical regardless of their true morphology, to be measured and accounted for (see Bamford et al. 2009). The net result is that the Galaxy Zoo classifications are an excellent match for results

from expert classification, and have produced science ranging from studies of red spirals (Masters et al. 2010) to investigations of spiral spin (Slosar et al. 2009). A full review of Galaxy Zoo science is beyond the scope of this review; a recent summary is given in the Galaxy Zoo 2 data release paper by Willett et al. (2013).

It is worth noting that some of the project's most important results have been the result not of interaction with the main classification interface, but represent rather serendipitous discoveries made by participants. We return to these in Section 5 below.

Surfaces of solar system bodies: Moon Zoo, Moonwatch. If studying galaxies remains, at least in part, a visual pursuit, then the same is certainly true of planetary science. NASA's Clickworkers[24], which asked volunteers to identify craters on the Martian surface, lays claim to be the oldest astronomical crowd-sourcing project. The consensus results matched those available from experts at the time, but failed to go beyond this promising start to produce results of real scientific value. More recently, interfaces inviting classifiers to look at the Moon, Mercury, Mars and Vesta have been launched and attracted significant numbers of classifications; however, although preliminary results have been promising(Kanefsky, Barlow & Gulick 2001) these projects have yet to produce datasets that have been used by the planetary science community in the same way that Galaxy Zoo has by the astronomical community. The recent release of the first paper from the Cosmoquest Moon Mappers project (Robbins et al. 2014) may indicate that this will change.

Tracking Features in Giant Planet Atmospheres: WinJUPOS Not all astronomical crowd-sourced visual classification is led by professional scien-

[24]http://www.nasaclickworkers.com/

tists. JUPOS[25] is an amateur astronomy project involving a global network of citizen observers to monitor the appearance of planetary atmospheres. Recent software developments have provided a much more quantitative perspective on these citizen observations. The WinJUPOS software[26] was developed by a team of citizen scientists led by G. Hahn; it allows multiple images of a giant planet to be stacked with a correction for the rapid rotation of Jupiter or Saturn (once every 10 hours), then re-projected onto a latitude-longitude coordinate system, so that the precise positional details of atmospheric features can be determined via "point-and-click," relying on the citizen's ability to identify features on the planetary disc visually.

By doing this over many nights surrounding Jupiter's opposition, the community builds up enormous drift charts, comprising tens of thousands of positional measurements, for these features, ranging from the tiniest convective structure being moved by the jet streams, to the largest vortices (e.g. Hahn 1996). The charts reveal the dynamic interactions within the jovian weather layer, and the long-term stability of their zonal jets (see e.g., the regular bulletins provided by the Jupiter section of the British Astronomical Association). The positions can be extrapolated forward in time, enabling targeted observations by professional observatories or even visiting spacecraft. The Juno mission, scheduled to arrive at Jupiter in 2016, is reliant on the citizen observer community to provide this sort of contextual mapping for the close-in observations from the orbiter. This long-term record of Jupiter's visible appearance by citizen scientists has proven to be an invaluable resource for jovian atmospheric scientists.

Time domain astronomy: Supernova Zoo and Planet Hunters The

[25] `http://jupos.privat.t-online.de`

[26] `http://jupos.privat.t-online.de`

three defining characteristics of "Big Data" have come to be accepted as volume, velocity and variety. Time-domain astronomy projects, that indeed require the immediate inspection of challenging volumes of live, high velocity, complex data, can benefit from citizen science, as shown by two recent projects, Supernova Zoo and Planet Hunters. While transients such as supernovae or asteroids can often be found through the use of automatic routines, visual inspection is still used by many professional science teams as part of their process of selecting candidates for follow-up.

The most successful attempt to use crowd-sourcing to attack these problems to date has been the offshoot of Galaxy Zoo described in Smith et al. (2011). Data from the Palomar Transient Factory (Law et al. 2009) was automatically processed and images of candidate supernovae uploaded on a nightly basis; this triggered an email to volunteers who, upon responding, were shown the new image, a reference image and the difference between the two. By analyzing the answers given by the volunteers to a series of questions, candidates were sorted into three categories, roughly corresponding to "probable supernova," "likely astrophysical but non-supernova transient" and "artifact." The results were displayed on a webpage and used by the science team to select targets for follow-up. Despite the Supernova Zoo site attracting many fewer classifiers than Galaxy Zoo, it was highly effective in sorting through data, with consensus typically reached on all images within 15 minutes of the initial email being sent.

The large dataset generated by this project was used by Brink et al. (2013) to develop a supervised learning approach to automatic classification for PTF transients. The performance of this routine, which for a false-positive rate of 1% is more than 90% complete, depends on the kind of large training set that

can be generated by crowds of inspectors; this suggests a future path for large surveys in which citizen science provides initial, training data and is followed by machines taking on the remaining bulk of the work. Encouragingly, Brink et al.'s method, which makes use of a set of 42 features extracted from survey images, has performance which is insensitive to a small fraction of mislabeled training data, suggesting that the requirements for accuracy of citizen science projects which aim to calibrate later machine learning may be less stringent than otherwise thought.

A different approach to crowd-sourced classification in time-domain astronomy is exemplified by the Planet Hunters project, which asks volunteers to examine light curves drawn from the dataset provided by the Kepler mission in order to identify interesting events in retrospect. While the task of identifying transits from extrasolar planets is, at first glance, one which seems more suited for automated than for human analysis, the success of Planet Hunters in identifying more than fifty planet candidates missed by the automatic routines suggests that there remains a role for inspection by eye in cases where the relevant science requires samples of high completeness. Several of the planets found by Planet Hunters are unusual: PH1b, the project's first confirmed planet (Schwamb et al. 2013) and a circumbinary, is the first planet known in a four-star system. Others, including the more than forty candidates identified in the habitable zone of their parent star by (Wang et al. 2013), might have been expected to be recovered by more conventional searches. Planet Hunters, therefore, is acting as an independent test of the Kepler pipeline's efficiency (Schwamb et al. 2012) and has inspired improvements in subsequent analysis (Batalha et al. 2013).

3.2 Classification Analysis

In most visual classification projects, working on archived image data with little time pressure, the random assignment of task to classifier, followed by simple, democratic treatment of the classifications has been judged sufficient. However, the need for rapid processing of images in time domain astronomy projects has prompted the investigation of more efficient analyses of the classification data. Using the Supernova Zoo project's archive as a test, Simpson et al. (2012) developed a Bayesian method, IBCC, for assessing classifier performance; in this view, each classification provides information both about the subject of the classification and about the classifier themselves. Classifier performance given subject properties can thus be predicted and an optimum set of task assignments calculated. Moreover, work by Simpson et al., as well as Kamar, Hacker & Horvitz (2012) and Waterhouse (2013) on Galaxy Zoo data, suggests that accuracy can be maintained with as few as 30% of classifications. This sort of optimization will be increasingly important for online citizen science, especially in projects that use a live stream of data, rather than an archive, since the classification analysis will need to be done in real time.

Rare event detection: Space Warps Steps towards real-time classification analysis have been taken in the Space Warps project.[27] Space Warps is a rare object search: volunteers are shown deep sky survey images and asked to mark features that look as though they are gravitationally lensed galaxies or quasars (Marshall et al, More et al in prep). Extensive training is provided via an ongoing tutorial that includes simulated lenses and known non-lenses, and immediate pop-up feedback as to whether these training images were correctly classified.

[27] `http://spacewarps.org`

Because real lenses are rare (appearing once every 10^{2-4} images, depending on the dataset), the primary goal is to reject the multitude of uninteresting images so that new ones can be inspected – and this drives the need for efficiency. Marshall et al (in preparation) derived a simplified version of the IBCC classification analysis that updates a probablistic model of both the subjects and the agents that represent the classifiers in a statistically online manner. This analysis was run daily during each of the Space Warps projects, and subjects retired from the stream as they crossed a low probability threshold. This algorithm is being implemented into the web application itself for future datasets.

The increased efficiency of visual classification projects that will come with real-time analysis will enable feedback on the projects' progress to be given much more promptly – an important part of the collaboration between professionals and amateurs in crowd-sourcing projects.

3.3 Visual Classification in Other Fields

Although, as described in the previous section, astronomical analysis led the development of citizen science as a data analysis tool, it has quickly been adopted by other fields. In some cases, this adoption has been explicit. The tools developed for Stardust@home were developed into a general purpose library for citizen science, BOSSA. Both this and the Zooniverse platform (which hosts many of the examples described above) support projects from fields as diverse as ecology and papyrology. This diversity allows general lessons about project design to be drawn; indeed, this is an active area of research for academic fields as diverse as computer science, economics and social science. A recent paper by Crowston & others (2014), for example, compares Planet Hunters and Seafloor Explorer, a

Zooniverse project which explores the health of fisheries off the coast of North America.

Projects from other fields can also suggest strategies which could be adopted by future citizen astronomy projects. In particular, future projects involving analysis of survey data which has been collected for a multitude of purposes may require a more sophisticated model for data analysis than the simple decision tree presented by projects such as Galaxy Zoo.

Snapshot Serengeti This Zooniverse project invites the visual classification of animals in photographs from more than two hundred motion-sensitive "camera traps" installed in the Serengeti National Park, and enables a particularly sophisticated volunteer response. Driven in part by the need for an interface which allows volunteers to state the obvious (for example, identifying elephants, lion or zebra) and also to provide more obscure classification (for example, distinguishing between different species of gazelle), a variety of classification paths are presented. In addition to just clicking buttons identifying species, volunteers can opt for a decision tree-like approach, or choose from a variety of similar species ("Looks like an antelope...") or search the descriptions provided in order to make an informed classification ("Show me all animals whose descriptions involve 'ears' "). This hybrid model has proved successful not only in encouraging classification, but also in encouraging learning; over a Snapshot Serengeti classifier's "career" they are increasingly likely to chose more direct routes.

Visual inspection of 3-D biological scans: Eyewire. Another aspect of project strategy, and design, relates to the engagement of the volunteers. The online citizen astronomy projects developed so far have tended to emphasise co-operation between volunteers, and the results being due to a team effort.

Elsewhere, experiments with a more competitive approach to citizen science, "gamifying" the activity, have been performed.

The Eyewire project[28], based at MIT, seeks to supplement machine learning identification of neurons in three-dimensional scans. Notably, this project incorporated some "gamified" elements into its design. Participants in the project, who are asked to identify connected regions throughout a three-dimensional scan, earn points based on participation and also have a separate, publicly visible, accuracy score. In addition to overall leader boards, the project also runs short challenges including a regular Friday "happy hour" in which participants compete on specific problems. Eyewire is also notable for its other strong community elements, with a chat room open and available to all participants in the project (supplemented, incidentally, by a "bot" built by a participant which answers frequently asked questions from new users). Its first result, which drew on mapping of so-called 'starburst' neurons, was published in mid-2014 (Kim et al. 2014).

4 DATA MODELLING

New understanding of the world comes from the interpretation – fitting – of data with a physical model. Such "data modelling" often involves technical difficulties that computers may find hard to overcome, associated with complex and/or computationally expensive likelihood functions. Humans, by applying their developed intuition, can contribute a great deal to the exploration of a model's parameter space by closing in quickly on those configurations that fit the data well. This process can be particularly satisfying, rather like solving a puzzle. Meanwhile, many "machine learning" techniques effective in one field can often

[28] www.eyewire.org

be adapted to astronomical problems: there are plenty of citizens with the skills to do this. How have citizen scientists been involved in model making and data fitting in astronomy, and other fields, to date?

The Milky Way Project Simpson et al. (2012) provided volunteers with a fairly flexible set of annulus-drawing tools, for annotating circularly-symmetric "bubble" features in colour-composite (24.0, 8.0 and 4.5μm) infrared images from surveys carried out by the Spitzer space telescope. These bubbles are hypothesized to have been caused by recently-formed high mass stars at the centre each. The (bubble) model in this case is simple and recognizable, making both the interface construction and its operation relatively straightforward. The large sample of bubble models have been used to investigate the possibility of further star formation being triggered at the bubble surfaces (Kendrew et al. 2012). A subsequent effort (Beaumont et al. 2014) used data provided by the project to train a machine learning algorithm, Brut, in bubble finding. Brut is able to identify a small number of sources which were not identified in the Simpson et al. catalog. These bubbles were difficult for humans to identify, owing to their lying close to bright sources, and so having low contrast relative to their surroundings.

In addition, Brut has proved effective at identifying suspect bubbles included in the previous (pre-citizen) surveys. Given the relatively small size of the MWP sample, the main use of machine learning here has been to provide an independent check on the citizen classification data; for larger samples, as discussed below, an approach in which machine learning is trained on citizen science data, and gradually takes over the classification task could be considered.

Modelling Lens Candidates The Space Warps project (Section 3.2) has an informal data modeling element. The classification interface is restricted to

enabling identification of candidate gravitationally-lensed features, but all the images are available via the project's discussion forum. A small team of volunteers (including several citizens who helped design the project) has engaged in modeling some of the identified lens candidates using web-based software developed and supported by the project science team.[29] Results from a small test program show that the model parameters derived by the ensemble of citizens are as accurate as those derived by experts (Kueng et al, in prep). A pilot collaborative modeling analysis was carried out and written up by a small group of Space Warps volunteers[30] (Capella_05 2014).

Galaxy Zoo: Mergers This has been perhaps the most advanced attempt at data modeling in astronomical web-based citizen science (Holincheck et al. 2010, Wallin et al. 2010). Here, simple N-body simulations of galaxy mergers were performed in a java applet, and the results selected according to visual similarity to images of galaxy mergers (previously identified in the Galaxy Zoo project). A key hypothesis here is that the inspectors of the simulation outputs would be able to find matches to the data more readily than a computer could, for two reasons. First is that humans are good at *vague* pattern matching: they do not get distracted by detailed pixel value comparisons but instead have an intuitive understanding of when one object is "like" another. The second is that initializing a galaxy merger simulation requires a large number of parameters to be set – and its this high dimensionality that makes the space of possible models hard to explore for a machine. Humans should be able to navigate the space using their intuition, which is partly physical and partly learned from experience gained from

[29] `http://mite.physik.uzh.ch`

[30] See `http://talk.spacewarps.org/#/boards/BSW0000006/discussions/DSW00008fr` for the forum thread that was used.

playing with the system. Initial tests on the marging system Arp 86 showed the crowd converging on a single location in parameter space, and that the simulated mergers at this location do indeed strongly resemble the Arp 86 system. The authors have since collected thousands of citizen-generated models for a sample of a large number SDSS merging systems (Holincheck et al, in preparation).

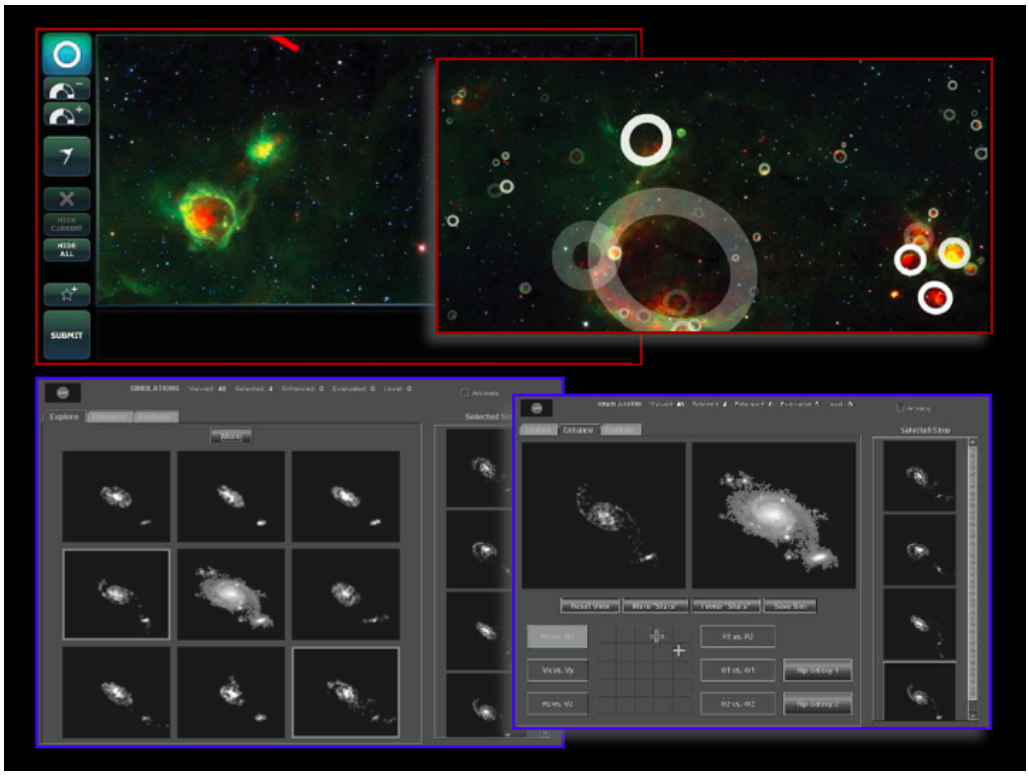

Figure 4: Examples of image modeling in web-based citizen science projects. Top row: star formation "bubble" identification and interpretation in Spitzer images in the Milky Way Project, with the annotation interface shown on the left, and some example (selected, averaged) bubbles on the right. Images from Simpson et al. (2012). Bottom row: matching N-body simulated merging galaxies to SDSS images in the Galaxy Zoo Mergers project (left), and exploring parameter space two parameters at a time to refine the models (right). Screenshots from Holincheck et al. (2010).

Protein Modeling with Foldit One of the most successful examples of crowd-sourced, "manual" data modeling is the online multi-player 3-D protein modeling game, Foldit (Cooper et al. 2010)[31] In this pioneering project, players compete in teams to find the best – lowest free energy – molecular structures for particular protein "puzzles." These puzzles are naturally visualizable in three dimensions, but they nevertheless involve thousands of degrees of freedom, in a parameter space that is notoriously hard to explore. Under the hood is the professional Rosetta structure prediction methodology; the player's scores are simply the negative of the Rosetta-computed energy. Foldit provides an accessible interface to the Rosetta toolkit, which provides multiple ways to interact with the protein structure as the global minimum energy solution is sought. The Rosetta model parameter free energy hyper-surface is completely analogous to the complex likelihood surface of any non-linear model, the kind of model that is to be found in planetary system dynamics, gravitational lenses, merging galaxies, and many other astrophysical data analysis situations.

Results from Foldit have been very encouraging, with the players discovering several new protein configurations, leading to improved enzyme performance (Eiben et al. 2012) and new understanding of retroviral drug design (Khatib et al. 2011b). The team have suggested several features of Foldit that appear to them to have underpinned its success. Recipes for manipulating the protein structures (that codify strategies) can be shared within teams, and later made available by the Foldit team to the whole community – these algorithms evolve rapidly as different players modify them, and can rival (if not out-perform) strategies developed by professional scientists (Khatib et al. 2011a). The game provides multiple

[31] `http://fold.it`

sources of motivation (competition between players, collaboration within a team, short term scores, long term status) which appeal to a variety of players.

Online Data Challenges We now turn to data modeling by citizens implementing machine learning techniques in astronomy, via analysis challenges organised by members of the professional astrophysics community. The measurement of weak gravitational lensing by large scale structure ("cosmic shear") relies on the measurement of the shapes of distant, faint galaxies with extreme accuracy. The STEP (Heymans et al. 2006, Massey et al. 2007) and GREAT (Bridle et al. 2010, Kitching et al. 2012a, 2013) blind galaxy shape estimation challenges have had an enormous impact on the field, revealing biases present in existing techniques, and providing a way for researchers outside the world of professional cosmology to participate. In particular, the GREAT08 challenge saw very successful entries from two (out of a total of 11) teams of researchers from outside of astronomy (albeit still professional researchers), including the winner. A companion, somewhat streamlined galaxy shape measurement challenge, "Mapping Dark Matter," which was hosted at the Kaggle website[32] (Kitching et al. 2012b). The wider reach of this platform led to over 70 teams making over 700 entries to the competition; many of the teams did not contain professional astronomers, although most were still from academia.

In a comparison with the GREAT challenges, the Kitching et al. found a factor of several improvement in shear accuracy over comparable previous challenges, and suggested two interesting explanations for this success. First, the challenge was designed to be as accessible as possible, with an extensive training set of data that needed very little explanation; in this way the challenge was geared towards

[32] `http://www.kaggle.com/c/mdm`

idea generation. Second, they noted that the competitive nature of the challenge (a webpage leaderboard was updated in real time as entries were submitted) seemed to stimulate the analysts into improving their submissions. Kaggle offers cash prizes, which will have had some effect as well (the pot was $3000 for this challenge, even if indirectly).

Two more astronomical Kaggle challenges have since been set. The first involved inferring the positions of dark matter halos based on their weak lensing effects (Harvey et al. 2014)[33] This challenge attracted the attention of 357 teams, perhaps due to its larger prizes, and led to an improvement in halo position accuracy of 30%. It also sparked some debate in its forums as to the design of the challenge: the models used to generate the data, the size of the test datasets (and consequent stability of the leaderboard), the choice of leaderboard metric and so on. These issues are also of generic importance for scientists looking to crowd-source algorithm development. It is interesting to note that the Kaggle forums are a useful resource for the Kaggle development team: the citizens who are active there do influence the design of the site infrastructure and challenge rules (D. Harvey, priv. comm.). The most recent Kaggle astronomy challenge was to reproduce the Galaxy Zoo crowd-sourced galaxy morphologies, given the same color images.[34] 326 teams entered this challenge ... (K. Willett, priv. comm.).

Like Foldit's "recipes," the Kaggle challenges are crowd-sourcing the development of new algorithms. As data science plays an increasingly important role in industry and commerce, we can expect the number of citizens interested in applying their skills to science problems in their spare time to grow. The challenge is to present those problems in meaningful ways, to enable high value contribu-

[33] `http://www.kaggle.com/c/DarkWorlds`

[34] `http://www.kaggle.com/c/galaxy-zoo-the-galaxy-challenge`

tions to be made. While members of this community may not identify as "citizen astronomers," there is clearly an opportunity for citizen data scientists to play an important support role.

5 CITIZEN-LED ENQUIRY

The previous sections have focused on specific, and somewhat isolated activities in which citizens have participated. In most cases, the community's involvement has been a *contribution* to a scientific investigation defined by professionals. The most important part of any scientific investigation is the question at its heart: what is it we are trying to find out about the universe? In this section we look at some cases where the process of enquiry, the science itself, has been instigated or led by citizens.

In principle, this is an area of great potential. The constraints of funding proposals and management of research groups can often mean that professional scientists focus very narrowly on particular topics of research, specializing in particular techniques or datasets. Steering away from this course implies taking risks with time management, and allocation of resources to an ultimately fruitless research area can be detrimental to careers. Citizen scientists are largely free of these managerial and budgetary constraints, and are able to devote their attentions to whatever topics interest them. Moreover, we might expect outsiders to ask some unusual questions, and make connections and suggestions that highly focused professionals may not have thought of. What are some enquiries that citizens have led in astronomy to date, and how have they been enabled and supported?

Saturn Storm Watch. In this project, Cassini's observations of light-

ning emissions were connected to active amateur observations of the convective cloud structures within the giant planet atmosphere (Fischer et al. 2011), and the vertices of Saturn's bizarre north polar hexagon (Godfrey 1988) (a 6-sided planet-encircling wave that has persisted for at least 30 years but that has only recently been observed, by amateur astronomers). In the first case, citizen scientists wished to identify the source of the radio emission detected by Cassini, after being alerted to them on the Planetary Virtual Observatory and Laboratory. [35] In the latter case, the long-term evolution of the hexagon vertices was used to understand what sort of wave this is, and to identify its origins.

The Galaxy Zoo Forum.

The best known serendipitous discovery emerging from the Galaxy Zoo project is "Hanny's Voorwerp" (Lintott et al. 2009), a galaxy-scale light echo which reveals a recent ($\sim 100,000$ years ago) shutdown of AGN activity in IC 2497, a neighboring spiral galaxy (Keel et al. 2012). The discovery of the Voorwerp was first recorded in the Galaxy Zoo forum a few weeks after the project started, and inspired a more systematic search for similar phenomena in other galaxies. This project, made possible by the deep engagement in the forum community of Galaxy Zoo science team member Bill Keel, succeeded in finding more than forty instances of clouds which appear to have been ionized by AGN activity, in systems a third of which show signs of significant drops in activity on a timescale of tens of thousands of years.

The ability of the Zoo volunteers to carry out their own research, moving far beyond the mere "clockwork" required by the main interface, is best illustrated by the discovery of the Galaxy Zoo Green Peas (Cardamone et al. 2009). These

[35] `http://www.pvol.ehu.es`

small, round and, in SDSS imaging, green systems are dwarf galaxies with specific star formation rates (SFR per unit mass) which are unprecedented in the local Universe, matched only by high-redshift Lyman-break galaxies. Volunteers not only identified these systems, but organized a systematic search and further review of them. This effort included the use of tools designed by SDSS for professional astronomers to acquire and study spectroscopic data.

While the discovery of the Peas demonstrates the exploration ability of the Galaxy Zoo citizen community, it is important to note that the simpler, initial interaction provided by the main classification interface was necessary in order to develop that community in the first place. The participants in the citizen scientists' investigation of the Peas did not arrive on the site wanting to dig into spectra or confident of their ability to do so; these were the results of their participation. The project acted as an "engine of motivation" in inspiring its participants to become more involved.

Lightcurve analysis on Planet Hunters *talk***.**

The data modelling examples of Section 4 all involved modeling infrastructure provided by either the project's developers or their science teams. Planet Hunters provides a case where citizens have carried out their own modeling analysis, using their own tools. Critical to this endeavour was the ability of a small, and increasingly expert, group of volunteers to identify objects worthy of further analysis. For Galaxy Zoo, the forum had served this purpose but, as as the project matured, participation in discussions became restricted to a small and decreasing fraction of the community. Planet Hunters was the first Zooniverse project to introduce an integrated discussion tool, known as talk. Classifiers were asked, after viewing each light curve, whether they wanted to discuss what they

had seen; more advanced users could then harvest interesting candidates from these posts. For example, the candidates presented in Lintott et al. (2013) were initially collated by volunteers.

Their involvement was not limited to collecting Planet Hunters candidates. Making use of the Kepler archive, these advanced users were able to investigate the full set of data for candidate stars, producing periodograms and making fits to transits to derive planet candidate properties. Some of this analysis, for example checking the Kepler field for background sources, can be carried out online with tools originally intended for professional astronomers, but much was done off line using Excel or other software.[36] Nor was this sort of work restricted to planet candidates; interesting variable stars, including several new RR Lyrae systems, and cataclysmic variables (e.g. Kato & Osaki 2014) have been discovered and analysed by Planet Hunters volunteers.

Galaxy Zoo: Quench. Examples such as those above show that advanced work is possible within distributed citizen science projects, but that this requires volunteers to take on such tasks themselves. In order to increase the number, and perhaps the diversity, of volunteers moving beyond simple classification, experiments have been conducted to provide more scaffolded experiences. One of the most ambitious was the Galaxy Zoo: Quench project (Trouille et al. in prep) which offered volunteers the opportunity to "experience science from beginning to end."

In this project, classification of a sample of potential post-merger galaxies selected from the main Galaxy Zoo sample was followed by open exploration of

[36]The expense of IDL licenses was a major barrier to further modelling; much software used by the Kepler team is written in this proprietary language.

both the classification data and the metadata for these galaxies (available from the Sloan Digital Sky Survey) by the volunteers, enabled by a "dashboard[37]." Thousands of users (around 20% of those who participated in the classification stage and discussion) led to the formulation of a set of astrophysical interesting conclusions; a small number of participants (10) collaborated on writing a paper (in preparation). These later stages required intensive support from professional scientists (and in fact it was constraints on their time that prevented earlier submission of the paper).

Quench demonstrated that a hierarchical approach, with simple tasks leading to more advanced analysis, can be successful in encouraging large numbers of volunteers to move beyond simple classification; the number participating in exploring the data was much higher as a percentage of participants than in Planet Hunters. However, once engagement with the literature (either by reading or writing) is required there remains no substitute for significant involvement by professionals.

6 UNDERSTANDING THE CITIZENS

Having surveyed some of the activities involving citizen scientists, we can now consider some questions about this community itself. Who participates in citizen science, and what motivates them?

6.1 Demographics

Who is participating in citizen astronomy? We might expect the demographics to vary with activity, and with the level of commitment required. We have

[37] `http://tools.zooniverse.org/#/dashboards/galaxy_zoo`

some understanding of at least the former division from two studies that were carried out approximately simultaneously, one of the community participating in Galaxy Zoo, and another of the American Association of Variable Star Observers (AAVSO). Raddick et al. (2013) surveyed the Galaxy Zoo volunteer community to investigate their motivations (Section 6.2 below), via a voluntary online questionnaire. The 11,000 self-selected Galaxy Zoo users identified as 80% male, with both genders having an approximately uniform distribution in age between their mid-twenties and late fifties. The authors point out that this is close to the US internet user age distribution, except for slight but significant excesses in numbers of post-50s males, post-retirement people of both genders, and a deficit in males under 30. The survey respondents also tended to be more highly educated than average US internet users, with most holding at least an undergraduate degree, and around a quarter having a masters or doctorate. Very similar findings were reported by Gugliucci, Gay & Bracey (2014) from a survey of COSMOQUEST project participants.

These findings can be compared with a survey of the members of AAVSO: Price & Paxson (2012) received over 600 responses (corresponding to about a quarter of the society's members). The education levels of the AAVSO repondents matches the Galaxy Zoo community very closely; the AAVSO age distribution is more peaked (in the mid fifties), with a similar post-60 decline but also a marked absence of younger people. The online nature of the Galaxy Zoo project seems to have increased the participation of younger (pre middle-age) people. Likewise, the Galaxy Zoo gender bias, while itself extreme, is less so than at AAVSO, where some 92% of survey respondents were male. One additional piece of information provided by the AAVSO survey is the profession of the variable star observers:

most (nearly 60%) of the survey respondents were found to be working in science, computer science, engineering and education.

The Galaxy Zoo and AAVSO communities differ by more than just the nature of their activity. The smaller AAVSO community is arguably more engaged in its research, in the sense that a larger fraction of its membership is active in taking observations and contributing to analyses. It would be very interesting to know how citizen scientist motivation varied with the level of participation: dividing the Galaxy Zoo community into volunteers that contribute to the forum and those who don't could be interesting; perhaps more so would be to repeat the analysis of Raddick et al. over a wide range of projects, and look for trends there. The emergent picture thus far, however, is of a well-educated (and often scientifically trained) but male-dominated citizen science community, whose female and younger membership is likely to have been, at least in part, enabled via projects being hosted online. Continuing to lower the barriers to entry for currently under-represented demographic groups would seem both important, and within reach.

6.2 Motivation

What motivates citizen scientists? The two demographic studies referred to above also covered this question; having previously (Raddick et al. 2010) identified 12 categories of motivation in an earlier pilot study, Raddick et al. (2013) asked the 170,000 Galaxy Zoon volunteers at the time to comment on how motivated they were by each of these categories, and which was their primary motivation. The 6% who responded gave consistent answers to those given by around 900 forum users who responded in a separate appeal, allowing conclusions about this

presumably more engaged sub-population to be drawn. A desire to *contribute* to science was found to be the dominant primary motivation, being selected by 40% of respondents. *Astronomy*, *science*, *vastness*, *beauty* and *discovery* were all motivation categories that were found to very important to the volunteers, while *fun*, *learning* and *community* were less important.

The AAVSO demographic survey (Price & Paxson 2012) found similar results: over a third of variable star observers cited *involvement in science and research* as their primary source of motivation. However, a similar number gave an *interest in variable stars* as theirs, perhaps reflecting a stronger focus on the science questions involved than is present in the Galaxy Zoo community. Both groups of citizen scientists are clearly quite serious in their reasons for taking part: their motivations are actually very close to those of professional scientists, as many readers of this review will recognize. Perhaps surprisingly, the participants in online data analysis citizen science projects seem to a large extent to be a distinct community from those who participate in more traditional amateur astronomical activities. Galaxy Zoo classifiers, for example, are not, for the most part, regular amateur observers.

While research on the skill, and conceptual understanding, that people aquire while participating in citzien science activities is still in its early stages, there are some hints that continued engagement is correlated with both performance in the task at hand, and understanding of the physics and astronomy underlying the task. Prather et al. (2013) offered Galaxy Zoo and Moon Zoo volunteers the opportunity to take questionnaires that tested their understanding of the astrophysics associated with each project, and found that performance on this questionnaire correlated with high levels of participation in the projects. In the

Space Warps project, the probabilistic model for the crowd includes a measure of each classifier's skill; a strong correlation is seen between a classifier's skill, and the number of images they have seen (Marshall et al, in prep.). It seems as though the skillful classifiers remain engaged in the project for a long time, while almost no long-term participants have low skill – an observation consistent with the volunteers being motivated by contributing to science.

6.3 Competition or Collaboration?

As seen in Section 3.3 and Section 4 above, non-astronomical projects may have much to teach us about "gamification" as a motivator – the inclusion, either explicitly or implicitly, of game-like mechanics such as scores, "badges" or other rewards, leader boards, and so on. The Foldit team present a strong case for games as drivers of activity in citizen science, and the Kaggle challenges depend on competition to stimulate engagement. What has been the experience in citizen astronomy so far?

An early experiment with Galaxy Zoo showed that the addition of a score de-incentivised poor classifiers, but also resulted in the best classifiers leaving, presumably having been satisfied once a top score was achieved. A recent study by (Eveleigh et al. 2013) of the Zooniverse's Old Weather project, which included basic rankings for classifiers, highlighted these dangers, identifying volunteers who were alienated by the addition of this game-like score.They felt discouraged when top scores could not be matched, and worried about data quality if the scoring scheme rewarded quantity of classifications rather than accuracy. Taking seriously the above finding that citizen scientists are motivated by a perception of authentic participation in research, it seems right to be cautious about introduc-

ing elements which are, or which are perceived to be, in tension with this primary motivation.

Furthermore, the introduction of a significant incentivizing scheme relies on an accurate model of what "correct" behaviour would look like. This may prove to be a significant barrier to accuracy if such a model is not available. For example, in Planet Hunters, such a model would not have included unusual systems such as PH1b. Where a strong incentive scheme results in near-uniform classifier behaviour, a loss of flexibility in later data analysis could be incurred. A strong comparison of the type of reward structure utilized by Eyewire and the approach used by projects such as Galaxy Zoo is needed, in order to inform future project design.

The surveys described in the previous section reveal a community of people many of whom may have left academic science behind as soon as they finished their education, but who still maintain a passion for astronomy and the boundaries of knowledge. Their thirst for new information, and the desire to be part of the scientific process drives them to actively observe the night sky or to participate in analysis of large datasets. For the more motivated people involved in citizen science, being part of a community, albeit a distributed one, brings great enjoyment and satisfaction. With the connectivity brought by the internet, there is a social aspect of citizen science that unites people with this shared interest, which may be far removed from their "normal" lives. However, *community* was not found to be a strong motivator for the Galaxy Zoo volunteers – but it is nevertheless very important for the Galaxy Zoo forum users. More recent Zooniverse projects have sought to widen participation in community discussion, hypothesizing not that it will more strongly motivate people, but because it will help

them make better contributions. Tests of hypotheses like this should be helpful in guiding citizen science project design.

7 THE FUTURE OF CITIZEN ASTRONOMY

During this review a picture has emerged of two types of very active and engaged citizen astronomy community, which we might label observers and classifiers. Although theses communities come together in differing ways (by self-assembly through local groups linked by national and international networks, or by joining online projects built by professional organisations), they have reached a similar degree of internet-enabled connectedness, both with each other and with the groups of professional astronomers with whom they collaborate. They also share the common motivation of being involved in, and contributing to, science. In this section we look ahead, to the next decade or so, and discuss the likely paths that citizen astronomy will take, as the available technology advances and professional astronomy evolves. In it we try to identify the niches that citizens might best occupy in this changing environment, and also some key challenges that those who find themselves planning citizen science projects are likely to have to face.

7.1 The Future of Citizen Observing

In professional astronomy, the wide field survey era is upon us: SDSS provided the data for Galaxy Zoo, and other, larger surveys are planned or underway. Key science drivers for projects such as LSST and the Square Kilometer Array include mapping cosmological structure back into the reionisation era, and further opening the time domain; these will yield datasets of significantly increased volume, throughput rates, and complexity. Follow up observations of new dis-

coveries made at greater depths will be made with giant facilities such as ALMA and the various planned Extremely Large Telescopes, while distributed arrays of robotic telescopes, operating in remote regions with excellent atmospheric conditions, and trained to observe a target in a regular fashion over multiple nights will be able to take advantage of wealth of new transient phenomena.

These future advances in technology may in one sense widen the gap between citizen scientists and professionals again. For example, networked telescopes capable of quasi-continuous observations over 24 hour periods could be used to develop a consistent high-quality dataset for cloud tracking on Venus, Mars or the giant planets; as the images would be homogenous, we can envisage automated software identifying morphological peculiarities over time, replacing the crowd-sourced citizen analysis currently underway. However, such an investment would require both international funding and considerable time and effort: the availability of citizen observers will remain a factor.

However, the advances in hardware becoming available to citizen observers suggest other roles they could play. Larger optics, more sensitive cameras, and spectral coverage extending to longer wavelengths in the infrared could permit citizen investigations of Uranus and Neptune, the Trans-Neptunian and Kuiper Belt objects, and a wider variety of bright variable stars. Transits of extrasolar planets in front of their parent stars would be permitted from modest observatories provided they had stable conditions. New platforms might also become available to the citizen scientist, including balloon-borne observatories that provide crisper and more detailed observations of astronomical targets. We may well see networks of citizen deep sky observers investigating new bright transients found in the wide field surveys, while continuing to expand their own surveys.

Aside from pushing the observational boundaries, one challenge that amateur astronomy may face is its own big data problem. For example, solar system video monitoring projects are likely to need automated feature detection of some kind; other observing campaigns may also generate more data than is easily manipulated. Will this community take to crowd-sourcing its visual inspection? The Zooniverse platform is currently being redeveloped to enable easy upload of images and launch of projects; such a facility may be used by citizen scientists as well as by professionals.

7.2 The Future of Crowd-sourced Visual Classification

The point at which human review of data is no longer necessary has been forecast for decades, but as we have seen above, the number of problems for which manual review of images or data is still carried out is considerable. Even if the proportion of data for which human inspection is necessary decreases dramatically over the next decade (due to advances in automatic analyses), the continued growth in the size of astronomical datasets should ensure that there remains plenty for citizen scientists to do.

Consider the example of optical transients. The LSST system overview paper (Ivezic et al. 2008) gives a conservative estimate of $10^5 - 10^6$ alerts per night. Even if, after automated brokerage, only 1% of these require human classification, then that still might lead to 10,000 objects requiring inspection and interpretation every night – roughly one every 100 seconds. Given the increased reliability, and likelihood of serendipitous discovery, provided by citizen inspection, we should take seriously the incorporation of open inspection into plans for LSST transients. Similar arguments (with large error bars) can be made for other surveys:

inspection of transients for LOFAR already requires some human intervention (Stappers et al. 2011).

Implicit in this way of thinking is the sharing of work between human and machine classifiers. A simple example of human-machine task allocation was mentioned in Section 3.2, where machine analysis of PTF images identified those that contained candidate supernovae needing inspection by volunteers. It is worth noting that the inclusion of human inspection changed the nature of the machine learning task; instead of optimising for purity (producing a small but accurately classified set of candidates), the task for machine learning became one of identifying a subset of the images which contained many false positives but also a complete set of all supernovae. In this example, human and machine classification proceeded in series rather than in parallel, but more complex interactions can be imagined.

The accuracy of machine learning typically depends on the quality of the training or "gold standard" data which can be provided for the problem in question. Citizen science projects can assist by providing training sets which are orders of magnitude larger than might otherwise have been available, while work by Banerji et al. (2010) established that the confidence intervals provided by classifications from multiple volunteers can also improve machine learning accuracy. Predicting human responses (in the form of probabilities of classification) is an easier task than straightforward sorting. We expect, therefore, intermediate-size surveys to benefit in the future from a "citizen science phase," in which data is classified by volunteers prior to the automation of the task. This pattern has already been followed by the PTF supernova project discussed above, but perhaps it is more useful to think of the citizen scientists as providing training sets on

demand, so that as conditions change from night to night, or the performance of the instrument evolves over time, a small percentage of the total data is always processed by humans in order to provide a constantly updated training set.

If we are using classifications of gold standard data to assess the performance of human classifiers, it is straightforward to include machine classification in the same system. In this way, the task of classification could be shared dynamically and in real time between machine and human classifiers, improving the efficiency of the system. Significant work has already been carried out for the nearly analogous problem of assigning tasks to an ensemble of imperfect machine classifiers whose characteristics are known and for Mechanical Turk-like systems where a fixed payment is provided for a task but the problem of adding in volunteers is significantly harder. For the machine-only case, each classification task can be treated as having a known cost (perhaps the processing time necessary for a given routine), but when assigning tasks to volunteers, who are able to leave whenever they like, other costs must be taken into account. In order to create a viable system, it is, in fact, necessary to measure how *interesting* a task or set of tasks is, and this requirement may conflict with the need for efficiency. As an example, consider a Galaxy Zoo-like system which assigned the hardest galaxies to the best classifiers. This would result in a steady diet of faint fuzzy objects for the best classifiers; if they are motivated in part by the variety of images seen, then such a system would tend to systematically drive away its best classifiers. A study of Snapshot Serengeti even revealed that seeing a more impressive image early in a classifier's career (as measured by the number of volunteers who added it to their list of favourites) tended to decrease the number of classifications received from that volunteer in the long run. Considering individual classifications

in isolation is clearly not sufficient; the entirety of a volunteer's career must be considered when assigning tasks. We should be wary of over-specialisation even when efficiency is paramount. Complexities like these indicate a clear need for research into novel systems for task assignment, in order to scale citizen science to the challenges of the next generation of surveys.

7.3 Advanced Citizen Activities in the Future

As we have seen in previous sections, volunteers can and do move beyond simple classification problems, and such behaviour could become increasingly important as the volume and complexity of astronomical data continues to increase. We can imagine providing user-friendly, web-based tools enabling fairly sophisticated data analysis to be performed by anyone with a browser. The experience documented above invites us to consider the possibility of teams of citizens performing analyses that currently require a significant amount of research student time. Checking survey images and catalogs for processing failures and fitting non-linear models to data are just two possibilities. Just as research students adapt and develop the tools they are first presented with, the Kaggle and Foldit experiences point strongly towards a model where citizens are also enabled to evolve their tools. Open source tool code is a minimal requirement in this model; finding ways beyond this to support citizen algorithm development seems to be likely to pay off.

In terms of supporting citizen-led enquiry, an example of best practice exists in the way that the Sloan Digital Sky Survey's sky server provided tools for both professional (or advanced) researchers alongside simplified versions aimed primarily at educational use. This structure has the twin benefits of providing

near-seamless transitions from simple to more advanced interfaces, and of providing extra pressure to make the resulting interfaces easily usable (something which benefits all users, not just citizen scientists!). Designers of science user interfaces for upcoming large projects would do well to bear these twin audiences in mind. Indeed, the more citizen-accessible the interfaces to the upcoming public wide-field survey databases can be made, the better chance we will give ourselves of enabling and supporting "bottom-up" citizen science.

This term, introduced by Muki Haklay and collaborators, represents an ambition to produce citizen science projects that are driven by the participants. Moving beyond the 'top down' structure of most astronomical citizen science projects is, as we have shown, a significant challenge - but one that is, perhaps, worth taking on.

7.4 The Future of Citizen Science

As well as enabling access to the data, citizen science projects looking to engage larger crowds of volunteers will likely face some other challenges. We might expect contributing to science via large international public datasets to appeal to citizens of many nations: while translation of project materials is simple, coordinating a scientific discussion across multiple language barriers could prove difficult. Having a critical mass of professional scientists interacting in each language would seem the most important factor. Even within a single language group, collaboration is difficult to achieve with very large numbers. The hierarchical system of citizen discussion moderators bridging the gap between science teams and the crowd has worked well in the Zooniverse projects, although it requires significant commitment and effort from the volunteer moderators. Access to pro-

fessional scientists can be somewhat improved by regular webcasts (as provided, for example, by the Galaxy Zoo science team); this provides at least partially the scientific dialogue that is most valuable to the citizen collaborators. Certainly these can supply much-needed feedback as to the utility of the citizens' efforts, as the professionals report on how the citizen-provided data is being used. We might imagine regular broadcasts from the projects providing the data as playing a significant role in motivating and sustaining a crowd of volunteers. However, for the foreseeable future it remains the case that astronomical surveys and other organisations will seek to use citizen science as a way of expanding the amount of science that can be done; systems which rely on significant intervention from paid professionals will likely fail (or at least be a luxury available to few). A focus on systems which can maximise scientific return and volunteer participation without substantial intervention remains necessary.

8 CONCLUDING REMARKS

Over the last two decades, citizen astronomy has undergone a period of rapid growth, primarily due to the sharp increase in the ease with which people can form communities and work together via the world-wide web. A number of very productive "Pro-Am collaborations" have formed, to observe a variety of bright astronomical objects in ways that capitalise on the flexibility, availability and skill of the amateur observing community. Professional-led visual classification projects have appeared, attracting three orders of magnitude more citizens to the field than were previously engaged in amateur observational research. Citizen-classified training sets have been used to improve the performance of machine learning approaches, suggesting that we should think in terms of "human-machine

partnerships." Citizens have been challenged to take part in data analysis tasks of increasing sophistication and difficulty, and experiments in professionally-guided "bottom up" citizen research have begun.

In this review, we have consistently seen that the best citizen science in astronomy has come from organised communities asked to play to their strengths, and which operate in niches insufficiently occupied by either professional observers or automated classification software. The citizen astronomers are passionate about the subject, and are encouragingly motivated by being of service to science. We must recognize that a critical feature of "citizen science" is the enabling of amateurs to make authentic contributions to the research topic in question: this in turn should drive us to seek out those tasks that cannot be done by other means.

The observational and classification citizen scientist communities are similar in their diversity regarding both their motivation and their ability to contribute; this diversity means that good citizen science projects are ones that provide both a low barrier to entry, but that also provide (or support the development of) tools that enable their emergent experts to maximize their contributions to science. Indeed, the most dedicated volunteers have proved capable of developing and using fairly advanced astronomical techniques, suggesting that we are likely to continue to see increasing numbers of citizens co-authoring papers in high impact research journals. While not everyone who takes part in a project would want to move to more advanced work, the opportunity to do so is important.

Each of the case studies presented in this review has been an experiment in citizen science: amateur and professional astronomers alike have had good ideas for ways to make use of the public's skills and abilities, tried them out, and made progress in astronomy – and in doing so revealed something about the how citizen

science can work. Human potential is vast: citizen astronomy seems to us to be an experiment well worth continuing. It has significant impact on the progress of our science, and on the participants whether they be sitting in a university office or in front of a home computer or mobile phone screen.

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