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 projects in astronomy and solar system science but sampling beyond those fields. In doing so, we look for ideas from which astronomy could benefit in the future. We consider contributions to science in the form of observations, data processing, data modeling and the design of new scientific inquiries, and from this experience derive some commonalities between the most successful projects, and use them to suggest some guidelines for future projects. The limits of citizen science are not yet well understood, but we make some speculations for citizen astronomy in particular.

TO-DO: Phil: #65 Work conclusions into abstract

CONTENTS

1 Introduction (2 pages)

The term "citizen science" refers to the activities of people who are not paid to carry out scientific research, but who make intellectual contributions to scientific research nonetheless.[1] They come from all walks of life, and their contributions

[1]In this review we differentiate between the data analysis that citizens carry out themselves, and distributed "grid" computing farmed out to computers owned by citizens, and omit the

are diverse, both in type and research area. This review is about the science 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 since been 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 on 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

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."

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 questions: How can the full potential of citizen science be realised in astronomy? What are the particular niches that citizen science can fill, in our field?

This review is organised as follows. Astronomy research typically starts with observations: so do we, in Section 2. We then proceed to consider visual classification, data modeling and finally citizen-led enquiry in Sections 3–5. With this overview in place, we review in Section 6 the literature on, and the collected experience of, the population of citizens who have taken part, or are currently taking part, in scientific research. We then turn to the future, and speculate on how citizens might contribute to astronomy there (Section 7). We make some concluding remarks in Section 8.

2 Amateur Observing (5 pages)

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 citizens making astronomical observations almost inadvertently. What astronomical data are the citizenry taking, and what is it being used for?

2.1 Active Observing (3 pages)

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. In this section, we review some of the citizen contributions to active observations of the night sky. "Passive" contributions will be described in Sections 2.2 below.

How is active citizen observing beneficial to astronomy research? The first key advantage is time availability: professional observatories are always oversubscribed, with resources ending up being concentrated on one area of sky, or on a few astronomical questions. Such observations are rarely tuned to the optimum timescales for other scientific enquiries. For example, determinations of meteor frequencies on short timescales (minutes), or slow evolution of giant planets on longer timescales (years and decades). In contrast, amateur observations can be frequent, repetitive, and long standing, and are naturally well sampled across the globe during an exciting event of interest.

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.

The third benefit is contextual. Professional observations often are 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, 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 Centre[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 Centre by a team of amateur observers affiliated with

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

the La Sagra Sky Survey at the Astronomical Observatory (Spain), and characterised by professional astronomers during its closest approach in February 2013 (e.g., **?**).

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 Central Bureau for Astronomical Telegrams (CBAT) (e.g., **?**). 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 (**?**). 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 (**?**), and has gone on to detect at least eight main belt comets (**?**). These early citizen science discoveries, followed up by professional astronomers, have generated new insights into the properties and variety of comets. In some cases, such as the discovery of Comet Shoemaker-Levy 9 (co-discovered by amateur observer D. Levy) before its collision with Jupiter (**?**), these discoveries revealed the dynamic and evolving nature of our solar system.

Beyond first detections, citizen observers can aid in the detailed characterisa-

tion of physical and orbital characteristics of these newly discovered solar system bodies, and amateur-led contributions are published via the *Minor Planet Bulletin*[4]. Photometric monitoring of an asteroid as it rotates provides information on the physical parameters, such as the shape, rotation rate and orientation; whereas 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 **?**, for a comprehensive review). In this case study, it is the global distribution of citizen observers and their long-baselines of observations that can yield new discoveries of minor bodies in our solar system.

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., Fig. 1. The long-term monitoring provided by the network of amateur astronomers provide 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 **?**). Those images can be used by amateurs and professionals alike to quantitatively study the zoology of activity; from measuring wind speeds from erupting plumes (**?**); investigating the strength and changes to the

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

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

large vortices (e.g., the 2006 reddening of Jupiter's Oval BA, **?**); to determining the life cycle of the belt/zone structure (**??**). For Saturn, a close collaboration between citizen scientists and Cassini spacecraft scientists has allowed correlation of lightning-related radio emissions detected by the spacecraft with visible cloud structures on the disc (known as Saturn Storm Watch) (e.g., **?**), which would not be 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 (**?**).

Video monitoring has been used 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 and storage of large datasets on some centralised server (see **?**, 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 (**?**); their regular bulletins describe the changing appearance of the banded structure, the emergence of new turbulent structures and weather

[6] www.astronomie.be/registax

[7] www.autostakkert.com

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

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 discrete cloud features can be used to study the super-rotation of the Venusian atmosphere and the occurrence of a mysterious ultraviolet absorber high in the planet's atmosphere (i.e., using near-UV filters). For example, the Venus Ground-Based Image Active Archive was created by ESA to provide contextual observations supporting the Venus Express mission (**?**). The Martian atmosphere, with its ephemeral clouds, seasonal CO2 polar ice cycles and dust storms, continues to prove popular among citizen observers, although these typically supplement 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 for 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 are used to maximise contrast between white clouds and the background and long exposure times of tens of minutes. Citizen monitoring of all of these worlds (summarised in Fig. 1) provides the long-baselines, flexibility and high frequency of imaging needed to understand the forces shaping their evolving climates.

Transient Events and Meteor Detection The increasing adoption of video

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

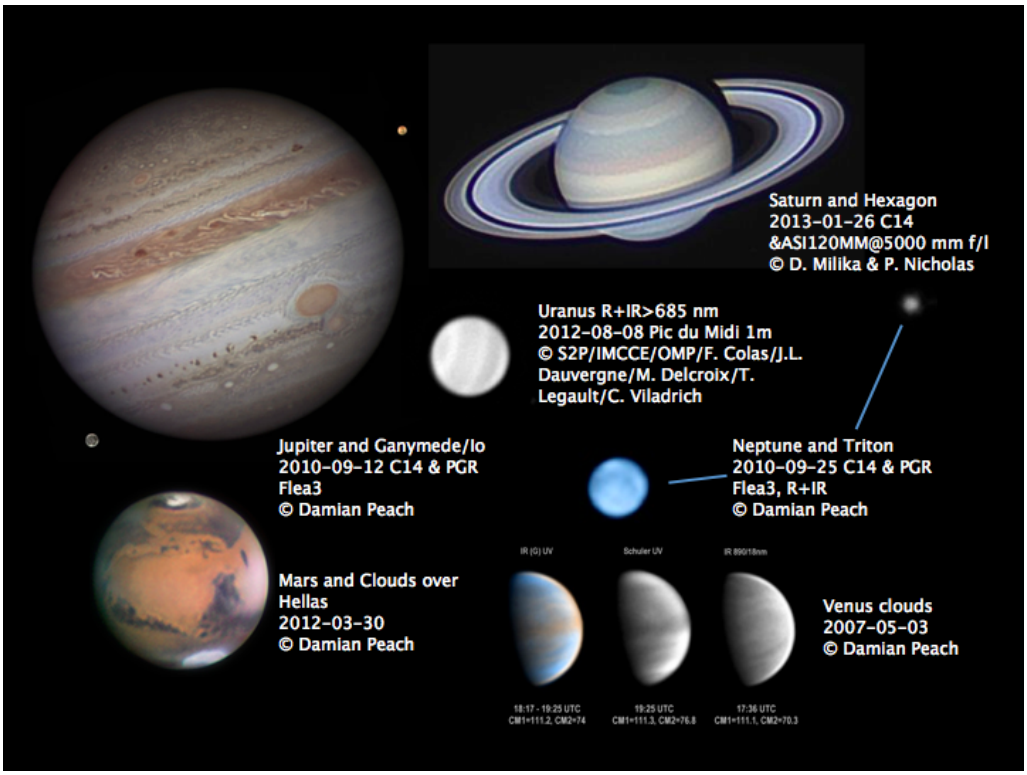

Figure 1: Examples of high fidelity images obtained by amateur planet observers.

monitoring of planetary targets means that unexpected, short-lived events are now more likely to be observed by citizen astronomers than by professional observatories. For example, an impact scar near Jupiter's south polar region was first discovered in imaging by Australian amateur Anthony Wesley on July 19th, 2009, and led to an international campaign of professional observations to understand the asteroidal collision that had created the scar (e.g., **???**). 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., **?**) (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

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

ALPO Lunar Meteoritic Impact Search for transient impact flashes recorded on the moon [11]).

Closer to home, citizen scientists play a crucial role in the recording of rare and unpredictable events such as the fireballs from meteoroid impacts, such as the February 2013 Chelyabinsk meteor (**?**). Video footage of the fireball and shockwave were essential to scientifically characterise the impactor and its likely origins, despite that fact that these records were largely captured accidentally by autonomous security cameras. Trajectories reconstructed from these records even permit the recovery of meteorites from a debris field (i.e., when the meteor survives the intense heat of atmospheric entry and reaches the ground). These objects are the remnant debris left over from the epoch of planetary formation, and fragments left over from comets and asteroids, so their numbers, sizes and composition provide a window onto 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 provided via a global network of citizen scientists, sharing and publicising their observations of meteors via the International Meteor Organisation (IMO[12]).

Exoplanet Transits. Beyond our solar system, amateurs have contributed to exoplanetary transit discoveries, attempting to measure the 1% diminution in starlight as a giant planet transits in front of its parent star. **?**) points out three methods where amateurs can contribute to characterising exoplanetary systems ? (i) by frequent observations of known transits to refine ephemeris; (ii) searching for transit time variations that can reveal additional planets in a system; and (iii) searching for previously unidentified transits in known planetary systems (e.g.,

[11] http://alpo-astronomy.org/lunaruplo ad/lunimpacts.htm

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

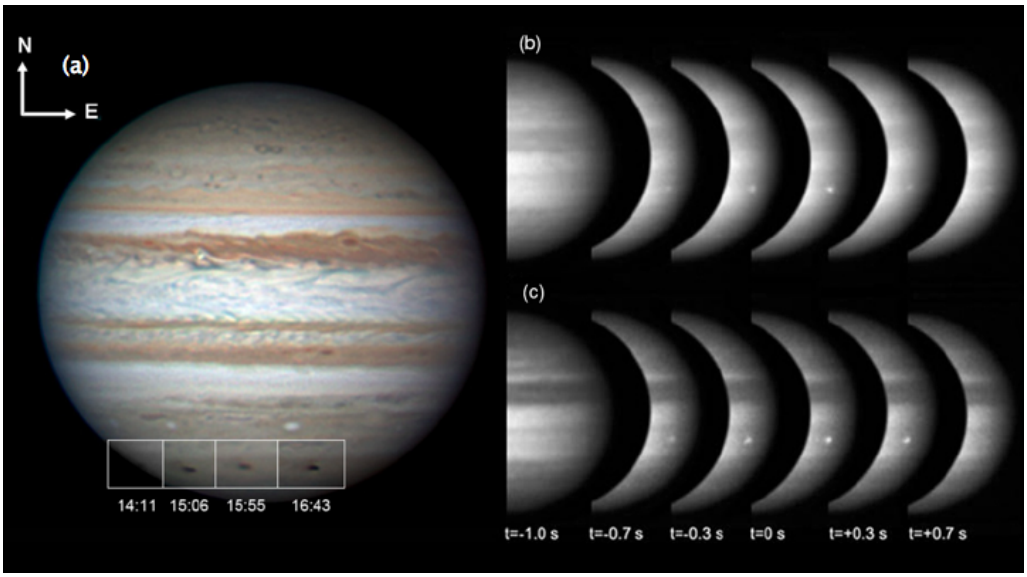

Figure 2: Citizen science contributions to monitoring of impacts in the Jupiter system. (a) Dark impact scar in Jupiter's atmosphere imaged by Anthony Wesley on July 19th 2009 (**?**). (b) The evolution of a smaller bolide impact on June 3rd 2010 at red wavelengths, also imaged by Wesley. (c) The evolution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

the discovery of the transit of HD 80606b from a 30 cm telescope near London, **?**).

Nearby Supernova Detection. **TO-DO: Chris: #19 Review nearby supernovae work.**

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.[13] The AAVSO provides a number of services to assist the volunteers,

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

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 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,[14] 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)[15] were used by Kloppenborg et al. (2010) to help interpret their interferometric imaging of the obscuring disk in the

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

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

system.

2.2 Passive Observing (1 page)

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. **?**) 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. **?** were able to astrometrically calibrate many of the images using their automatic image registration software, `astrometry.net`, which relies on background stars. This had been enabled as a Flickr "bot," crawling over all images submitted to the `astrometry.net` group 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, 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 statistical sampling can be developed - with ecological surveys of images submitted to sites like Flickr likely in the next few years.

Detecting Meteor Showers with Twitter. By saving a nightly (?) log of all tweets submitted to the web service Twitter, **?**) were able to detect several new meteor showers simply by searching for the text string "meteor." Unwitting naked-eye observers had spotted shooting stars and tweeted about them, giving rise to a detectable signal in the steam of tweets that night. The detected sample is incomplete/unlocalised/ etc... However, this work illustrates the potential both of Twitter as a communication system for connecting large numbers of observers with a science team, and of networks of unequipped observers for doing very bright object transient astronomy.

TO-DO: Chris: #23 Condense Geert's Twitter study, add meteor tracking app, move Chelyabinsk meteor mention to here

3 Visual Classification (6 pages)

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 datasets are made available to crowds of citizens, who are asked to inspect astronomical images, 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 Visual Classification in Astronomy (3 pages)

Stardust@home While significant preliminary work had been carried out by NASA's clickworkers project (see below), the project that first illustrated the potential of crowd-sourcing for astronomical purposes was Stardust@home[16]. This effort, which asked volunteers to scan through images of samples returned from Comet Wild-2 by the Stardust mission, attracted a large audience to the apparently 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 (see next section), and featured a stringent test which had to be passed before classifications were 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, at least one later proving an excellent candidate for an interstellar grain. Perhaps the most significant long-term impact of Stardust@home, though, was the demonstration that large amounts of volunteer effort were available even for relatively 'unsexy' tasks such as hunting dust grains which do not involve intrinsically beautiful images, and that, with a suitable website design and stringent testing, scientifically valuable results could be obtained.

[16] http://stardustathome.ssl.berkeley.edu/

TO-DO: Chris: #30 Add Stardust@home references, Stardust@home url as a footnote.

Galaxy morphology with Galaxy Zoo These results 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 amongst others de Vaucoleurs, it remains the case that the morphology of a system is closely related to – but not entirely defined by – parameters such as colour, star formation history, dynamics, concentration and so on. In an effort to prepare for large surveys such as the Sloan Digital Sky Survey (SDSS), Lahav et al. (1995) and Lahav et al. (1996) followed especially by the work of Ball et al. (2004) developed neural networks trained on small samples of expert classifications in order to automate the process of classification,[17] arguing that the size of the then up-coming surveys left no place for manual classification.

TO-DO: Chris: #32 Add real refs for automatic morphology classification

The performance of the 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 particularly 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 classifiers.

[17]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

Schawinski (Schawinski et al. 2007) and Nair (Nair & Abraham 2010), amongst others, spent substantial time during their time as graduate students classifying tens of thousands of galaxies.

Inspired by Stardust@home, a group led by one of the authors (Lintott) created Galaxy Zoo in 2007 to provide basic classifications of SDSS galaxies[18] 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: 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 doing something real soon after arriving at the site; this approach, in contrast to Stardust@home where a difficult test needed to be completed before authentic and useful contributions could be made, 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. **TO-DO: Chris: #34 Insert box diagram illustrating Zooniverse tactics / GZ2 results.** 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.

TO-DO: Chris: #35 Add galaxy zoo participation statistics.

These figures are undoubtedly impressive, but they would be meaningless if

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

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 **?**), was sufficient.

Phil: By what criteria was it sufficient?

TO-DO: Chris: #68 Check consistency between sections: there are lots of "see below" type statements in this section.

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.). 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.) to investigations of spiral spin (Slosar et al.).

TO-DO: Chris: #36 Let's back up the accuracy claims here with some citations and numbers.

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. However, it is worth noting that many of the project's most important results have been the result not of interaction with the main 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, 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, but although preliminary results have been promising 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.

TO-DO: Chris: #38 Fact-check the consensus with experts claim about clickworkers, provide clickworkers reference.

TO-DO: Chris: #69 Tidy up the multiple mentions of clickworkers. Whats the optimal ordering of these sections given their inter-references?

Tracking Features in Giant Planet Atmospheres: WinJUPOS JUPOS[19] 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[20] 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,

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

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

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.

By doing this over many nights surrounding Jupiter's opposition, the team builds up enormous drift charts for these features (comprising tens of thousands of positional measurements), 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 orbiting spacecraft). This long-term record of Jupiter's visible appearance by citizen scientists has proven invaluable for jovian atmospheric scientists.

Time domain astronomy: Supernova Zoo and Planet Hunters **?**) describe the three ways – volume, velocity and variety – in which the analysis of "Big Data" can be challenging. Time-domain astronomy projects, that require the immediate inspection of challenging volumes of live, high velocity, complex data, can benefit from citizen science, as shown in these two recent projects. While transients such as supernovae or asteroids can often be found through the use of automatic routines, visual inspection is still used by many teams as part of the process of selecting candidates for follow-up.

TO-DO: Chris: #70 Provide citation for "3 V's" of big data

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) "Supernova Zoo." 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 subtraction between the two. By analyzing the answers 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 to select targets for follow-up. Despite the site attracting many fewer classifiers than the main 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 provided by citizen science and suggests a future path for large surveys in which citizen science provides initial, training data followed by machines taking on much of the work. Encouragingly, the routine, 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 time-domain astronomy through citizen science 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 extra-solar 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 completeness of classifications. While several of the planets found by Planet Hunters, including the project's first confirmed planet (PH1b, Schwamb et al.), are unusual – PH1b, 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 Ji et al., 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.) and has inspired improvements in subsequent analysis (Bathalia et al.). More recently, advanced users have participated in the identification of unusual stellar properties - see XXXXXXXX.

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 analysis of the classification data. Using the supernova project's archive as a test, **?**) 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. For systems involving tens of thousands of classifiers and perhaps a similar volume of subjects to be classified, an exact solution is computationally extremely expensive, but a MCMC approach can be used to find efficient solutions. Work by Simpson et al., as well as Horvitz et al and Waterhouse 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, and 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. Analysis strategies which require re-optimisation of the entire subject and agent model using all past classifications will likely be prohibitively expensive, and so the focus will need to be on "progressive" strategies that approximate the full inference.

Rare event detection: Space Warps Steps towards real-time classification analysis have been taken in the Space Warps project. 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 (Marshall 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. 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 clas-

sifiers in a statistically online manner (Marshall et al, in prep). 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 enables 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 (Chris, Phil, 1 page)

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, which has recently been ported to python as PyBOSSA, and the Zooniverse platform which supports many of the examples described above includes projects from fields as diverse as ecology and papyrology. This diversity of projects 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.

TO-DO: Chris: #73 Add citation to Crowston paper on PH and Seafloor Explorer

Projects from other fields can also suggest strategies which could be adopted by future astronomical 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 enables the analysis of images from more than two hundred motion-sensitive "camera traps," offers a particularly sophisticated 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 types 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 ("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.

TO-DO: Chris: #43 Move SS to GZ section endnote? Include Snapshot Serengeti citations

Phil: Is the SS experience relevant to open ended exploration of survey images? I've wondered for a while whether diagnosis of astronomical image reduction problems could be done by crowd-sourcing: DES do a lot of visual inspection just within their team, LSST could serve a larger volume to more people, potentially. The viewer ubrets with their shareable URLs seem vital for this; might SS-style interfaces also be important?

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.

Visual inspection of 3-D biological scans: Eyewire. This project, 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).

4 Data Modelling (4 pages)

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 often contribute a great deal to the exploration of a model's parameter space by closing in quickly on the model configurations that fit the data well. This process can be particularly satisfying, rather like solving a puzzle. 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, which are hypothesised to have been caused by a recently-formed high mass star at the centre of the bubble. The (bubble) model in this case is simple and recognisable, making both the interface constructions 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 are excluded from the Simpson et al. catalogue, and which are difficult for humans, specifically bubbles near bright sources which have low contrast relative to their surroundings. In addition, Brut proved effective at identifying suspect bubbles included in the previous surveys. Given the relatively small size of the MWP sample, the main use of machine learning is to contribute an independent check on the data; for larger samples, as discussed below, an approach in which machine learning trains on citizen science data and gradually takes over the classification task could be considered.

Modelling Lens Candidates The Space Warps project[21] 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

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

several citizens who helped design the project) has engaged in modeling the identified lens candidates using web-based software developed and supported by the project science team.[22] Results from a small test programme show that the model parameters derived by the ensemble of citizens are as accurate as those derived by experts (**?**). A pilot collaborative modeling analysis was carried out and written up by a small group of Space Warps volunteers[23] (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). **TO-DO: Chris: #49 Check through the merger zoo case study, ensure refs are up to date.** 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 proposal in this project 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 initialising 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 playing with the system. Initial tests on Arp 86 showed the crowd converging on a single location in parameter space,

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

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

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).

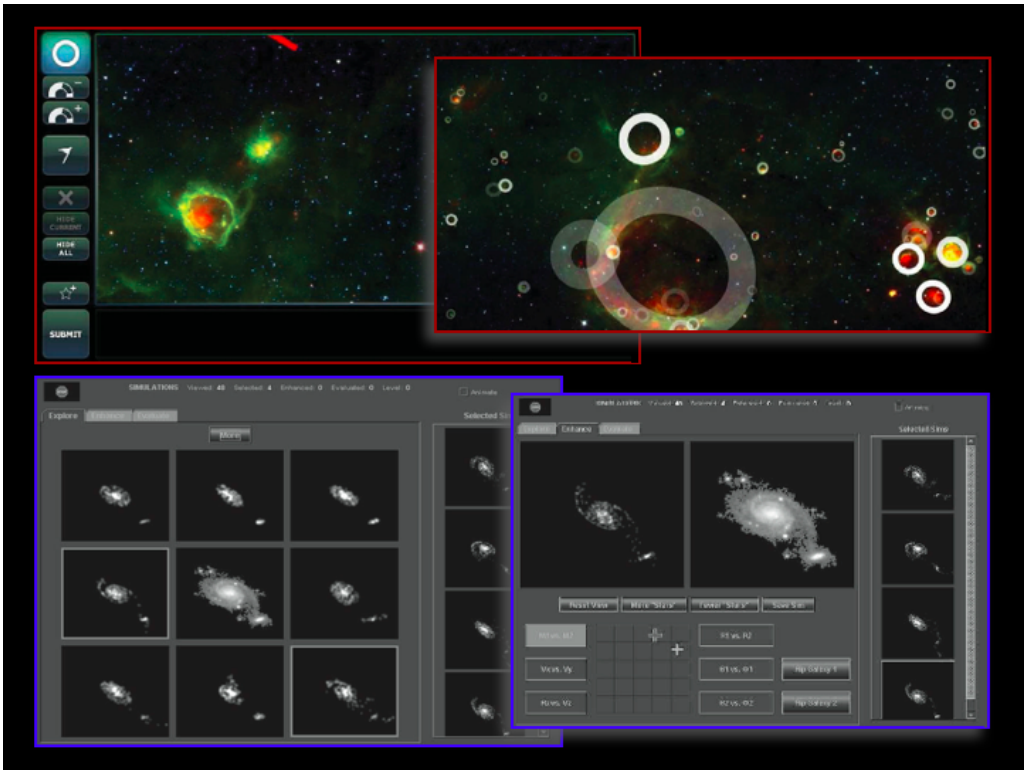

Figure 3: Examples of image modeling in web-based citizen science projects. Top row: star formation "bubble" identification and interpretation in Spitzer images in the Milky Way Project, with the annotation interface shown on the left, and some example (selected, averaged) bubbles on the right. Images 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).

Online Data Challenges A very interesting case of citizens being involved

in astronomical data modelling is that of the 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 (including the winner) from two (out of a total of 11) teams of researchers from outside of astronomy (albeit still professional researchers). A companion, somewhat streamlined galaxy shape measurement challenge, "Mapping Dark Matter," which was hosted at the Kaggle website[24] (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 *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

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

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)[25] This challenge attracted the attention of 357 teams, perhaps due to its larger prizes, and led to an improvement in position accuravy 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.[26] 326 teams entered this challenge ... (K. Willett, priv. comm.).

TO-DO: Phil: #52 Update Kaggle section with Galaxy Zoo challenge. Ask Kyle for spiel: what do we know about who entered? Astronomers or not? Note on winning method: convolutional neural networks. Then, a note on how performance of machines compares with crowds. Conclusion?

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

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

5 Citizen-led Enquiry (3 pages)

The previous sections have focused on specific, and isolated, activities in which citizens have participated. In most cases, the community's involvement has been a *contribution* to a scientific investigation, while not being involved in the design of that investigation. 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, 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, using a particular technique for which they become known. 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: 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 lightning emissions are connected with active amateur observations of convective cloud structures within the giant planet atmosphere (Fischer et al. 2011), and the tracking of 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. [27] In the latter case, the long-term evolution of the hexagon vertices is being 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.), a galaxy-scale light echo which reveals a recent ($\sim$ 100000 years) shutdown of AGN activity in IC 2497, the neighboring spiral galaxy. 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 of Galaxy Zoo science team member Bill Keel in the forum community, succeeding 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. **TO-DO: Chris: #63 Add more citations for voorwerp science?**

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 Peas. These small, round and, in SDSS imaging, green systems are dwarf systems 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, including using tools

[27] http://www.pvol.ehu.es

designed by SDSS for professional astronomers to acquire and study spectral data.

The discovery of the Peas marked the first time the Galaxy Zoo team realized the potential of the community of citizen scientists the project had acquired, but it is important to note that the simpler, initial interaction provided by the main 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.

Galaxy Zoo: Quench. Participants in citizen science projects like Galaxy Zoo and Saturn Storm Watch are highly motivated but geographically widely distributed; the impact of the internet in enabling them to find each other and collaborate is remarkable. The most recent Zooniverse astronomy project, Galaxy Zoo: Quench, is actively encouraging citizen-led enquiry, by providing flexible tools for investigating not individual objects but samples of galaxies classified in the main Galaxy Zoo project. It is an experiment in citizen-driven scientific investigation, and we await its results with interest.

TO-DO: Chris: #55 Write up Galaxy Zoo Quench...

Lightcurve analysis on Planet Hunters Talk. The data modelling examples of the Section 4 all involved modeling infrastructure provided by either the project's developers or their science teams. Planet Hunters is a case where citizens have carried out their own modeling analysis, using their own tools. A small group [?] of volunteers downloaded full Kepler lightcurve datasets for the best [?] community-selected candidates, and fitted transit lightcurves to them

using [?].

TO-DO: Chris: #51 Add text to PH talk case study: What did the super-users actually do in the way of advanced lightcurve modeling? Did it make it to the paper? References. This seems to me like something of a triumph, we must give it a good airing!

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 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 community of observers and society 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; it was the primary motivation for Raddick et al. Having previously (Raddick et al. 2010) identified 12 categories of motivation in an earlier pilot study, Raddick et al. (2013) asked the 170,000 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 around 900 forum users who responded in a separate appeal, allowing us to draw conclusions about this presumably more engaged sub-population. 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 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 connected to 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 skill, and both the number of images 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 citizen scientists being motivated by contributing to science.

6.3 Competition or Collaboration?

As seen in Section 3.3 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. 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. of the 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, feeling discouraged when top scores could not be matched, or worrying about data quality if the scoring scheme rewarded quantity of classifications rather tham 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 introducing 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 a significant barrier both 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) and, where a strong incentive scheme results in near-uniform classifier behaviour, a loss of flexibility in later data analysis. 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 maintained a passion for astronomy and the boundaries of knowledge. Their thirst for knew 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, that brings great enjoyment and satisfaction. With the connectivity of the internet, there is a social aspect of citizen science that unites people with shared interests. These pastimes and hobbies are often far removed from someone's "normal" life. 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 motivate people better, but because it will help them make better contributions. Citizen scientists, like professional scientists, are primarily motivated by getting science done.

7 The Future of Citizen Astronomy (7 pages?)

TO-DO: Chris: #58 Write up possibilities of future citizen astronomy.

TO-DO: Phil: #60 Write up challenges of future citizen astronomy.

Through this review a picture has emerged of two very active and engaged communities of citizen astronomers, the observers, and the classifiers. Although they have 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 are now collaborating, and 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 path that citizen astronomy will take, as the available technology advances and professional astronomy

evolves. In it we try to identify the niches that citizens can best occupy in this changing environment, and also some key challenges that those planning citizen science projects are likely to have to face.

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, LOFAR and the Square Kilometer Array are mapping cosmological structure back into the reionisation era, and further opening the time domain, projects that will yield datasets of significantly increased volume, throughput rates, and complexity. Follow up observations of new discoveries made at greater depths will be made with giant facilities such as ALMA and various planned Extremely Large Telescopes, while distributed arrays of robotic 1m+ class 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 hours could be used to develop a consistent high-quality dataset for cloud tracking on Venus, Mars or the giant planets, or to monitor for meteor showers to permit 3D trajectory reconstruction. As the images would be regularised, we could envisage automated software to track features, detect impacts, identify 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.

...

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 cold and icy bodies in the distant solar system (e.g., Trans-Neptunian objects and the Kuiper Belt), and asteroids and solar system debris closer to home. 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 rising up and out of the majority of the atmospheric turbulence to provide crisper and more detailed observations of astronomical targets. We may well see networks of citizen deep sky observers investigating new transients found in the wide field surveys, at least at the bright end.

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?

Chris: This could be a place to add a note about your Google project: it could in principle enable the citizen observers to enlist other citizens to help with interpreting their observations, no?

Phil: Revisit this observing section post-AVSO text...

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, 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 produce 10,000 images requiring inspection every night – roughly one every 100 seconds. Given the increased reliability and likelihood of serendipitous discovery provided by review by citizen scientists, 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: review of transients for LOFAR already requires some human intervention.

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 are possible. The accuracy of machine learning typically depends on the quality of the "gold standard" data

which can be provided for the problem in question, and, although citizen science projects can assist by providing training sets which are orders of magnitude larger than might otherwise have been available, work by Banerji et al. (2010) established that the confidence intervals provided by classifications from multiple volunteers can also improve 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.

This approach is complementary to the work discussed in Section 3.2, which mentioned efforts to improve the efficiency of classification projects by assigning tasks more efficiently. If we are using classifications of gold standard data to assess the performance of human classifiers, it is trivial to include machine classification in the same system. In this way, the task of classification could be split in real time between machine and human classifiers. 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 (XXXX REF XXX) 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 (XXXX REF XXXX). 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.

We therefore expect the development of novel systems for task assignment to be necessary to scale citizen science to the challenges for the next generation of surveys. Existing data from both Zooniverse and other projects can help investigate possible schemes, but early experiments suggest that assigning a "cost" to a single classification will not be easy. For example, one might propose that the number of classifications contributed after seeing each image might be a reasonable measure of the "cost" of a classification, with the expectation that seeing an especially interesting image might prolong a classification session. For most Zooniverse projects, though, there is little statistical significance in this measure. 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. Put more simply, we should be wary of over-specialisation even when efficiency is paramount.

As we have seen in previous sections, volunteers can and do also move beyond simple classification problems, and such behaviour could become increasingly important as the volume and complexity of astronomical data continues to increase. We might 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.

Enabling these advanced activities at the required scale could require the appearance of a significantly increased cohort of advanced online citizen scientists, many of whom would need to be fluent in the tools of professional astronomy. 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 projects such as LSST 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 citizen-led enquiry.

Chris: Do you want to add anything here about bottom-up citizen science?

As well as enabling access to the data, citizen science projects looking to en-

gage larger crowds of volunteers will likely face some other accessibility challenges. We might expect contributing to science via large international public datasets to appeal to citizens of many nations: 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, despite requiring significant commitment and effort from the volunteer moderators. Access to professional 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.

Chris: See what you think about the above. What would you add about the future of citizen science?

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 on the internet. 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.

In this review, we have seen that the best citizen science in astronomy has come from organised communities given freedom to explore, who can operate in niches not occupied either by professional observers or automated classification software. The citizen astronomers are passionate about the subject, and motivated by being of service to science. We therefore argue 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 drives us to seek out those tasks that cannot be done by machines or professionals. We have then seen something of the ability of citizen science to improve the performance of both machine learning and professional observing projects: it makes sense to think in terms of "human-machine partnerships" or "Pro-Am collaborations."

Both the observational and classification communities are very diverse in both motivation and ability to contribute; this diversity means that good citizen science projects are ones that provide both a low barrier to entry, while also providing (or supporting 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 we are likely to continue to see the numbers of citizens co-authoring papers in high impact research journals increase.

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