GALAXY ZOO: MORPHOLOGICAL CLASSIFICATION AND CITIZEN SCIENCE

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ABSTRACT

We provide a brief overview of the Galaxy Zoo and Zooniverse projects, including a short discussion of the history of, and motivation for, these projects as well as reviewing the science these innovative internet-based citizen science projects have produced so far. We briefly describe the method of applying en-masse human pattern recognition capabilities to complex data in data-intensive research. We also provide a discussion of the lessons learned from developing and running these community-based projects including thoughts on future applications of this methodology. This review is intended to give the reader a quick and simple introduction to the Zooniverse.

Subject headings: astronomical databases, methods: data analysis, galaxies: general, galaxies: spiral, galaxies: elliptical and lenticular, galaxies: statistics

1. A BRIEF HISTORY OF GALAXY MORPHOLOGY

One of the fundamental facts of the Universe is that most large galaxies¹ come in two basic shapes which astronomers call “Spirals” and “Ellipticals”. The exact details of why this is the case, and how the two types of galaxies relate to each other, remains a major mystery for astronomers. It is central to our understanding of how the creation and evolution of galaxies proceeds with cosmic time and depends on their cosmic location. Significant effort has been spent over the last few decades trying to address these questions.

Edwin Hubble was one of the first astronomers to attempt to systematically address the origin of the shape, or morphology, of galaxies using his famous “Hubble Sequence” or “tuning fork” diagram (Hubble 1926) which is still in use today (see Figure 1). Starting on the left, Hubble classified the elliptical galaxies using the observed ellipticity of the galaxy projected on the sky, giving them a numerical value associated with how round they appeared on the sky. In three dimensions, ellipticals can be triaxial objects, taking a range of morphologies from purely spherical systems through to flattened rugby ball shaped galaxies. On the right side of the tuning–fork, Hubble placed spiral or disk galaxies. These galaxies have a central “bulge” of stars, that resemble elliptical galaxies in some ways, embedded in a thin disk of stars that show a range of spiral patterns or “arms”. Hubble ordered disk galaxies based on the tightness of these spiral arms and the size of the central bulge. He had two distinct populations of disk galaxies, namely with and without a central bar-like (or linear) structure. At the point where these different classifications met (for spirals with the largest bulges, and tightest wound arms), Hubble placed “lenticular” galaxies which at the time were hypothetical disk galaxies with very large bulges and no spiral arms – they have since been found.

It is a common misconception that Hubble believed the “tuning fork” diagram was an evolutionary sequence, with elliptical galaxies on the left evolving along the sequence to form disk galaxies. In fact Hubble advised that “temporal connotations are made at one’s peril” in an early defence of the classification sequence (Hubble 1927), going on to say that he set up the classification “without prejudice to theories of [galaxy] evolution”. This misconception about Hubble’s beliefs probably arose due to his suggestion of the use of “early” and “late” types to describe the progression towards the right along the sequence (although he discussed that this nomenclature was simply for convenience and borrowed terminology commonly used for stellar classification, (Hubble 1926)). Astronomers still call elliptical galaxies “early” types and disk galaxies “late” type galaxies, although we now know that most “late” type galaxies have much younger stellar populations (ironically more “early” type stars) than most “early” type galaxies.

Since Hubble, there have been several updates to his classification scheme (for a recent review see Buta 2011) but key features have remained unchanged. What has changed dramatically is the number of galaxies catalogued and requiring classification. Before the advent of digital detectors in astronomy, astronomers could just visually classify the galaxies they saw via their telescopes and/or on photographic plates. New astronomers were trained to follow the classification rules and provided detailed morphologies for thousands of galaxies. Several large catalogues of nearby galaxies with such classifications exists (e.g. The Hubble Atlas of Galaxies (Sandage 1961), or the Third Reference Catalogue of Bright Galaxies (RC3), (de Vaucouleurs et al. 1991)), and many of these classifications are collected in the NASA/IPAC Extragalactic

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¹ A galaxy is just a collection of stars; typically billions for a large galaxy.
A T-type is a numerical coding of the Hubble Sequence increasing from negative numbers for ellipticals and lenticulars, through 0=S0/a, 1=Sa, 3=Sb, 5=Sc and so on.

Database\(^2\)

The expert classifier approach quickly became inappropriate with the digital surveys because of the size of the galaxy samples available; for example, the Main Galaxy Sample of the Sloan Digital Sky Survey (SDSS; York et al. 2000) Strauss et al. 2002 is over a million galaxies and simply cannot be visually inspected by any one astronomer (or even all the astronomers in the world working together). It became clear that some automatic method for classifying galaxies was needed, but programming a computer to recognise the complexities of galaxy shapes (spiral arms, bars, disk plus bulges) is very challenging.

The first attempts at an automated classification scheme included the use of artificial neural networks, e.g. Lahav et al. (1995) began this work by comparing the classifications of 830 galaxies from a set of six independent experts (R. Buta, H. Corwin, G. de Vaucouleurs, A. Dressler, J. Huchra and S. van den Bergh). These experts were unanimous in their classification in only 1% of objects, while an agreement of 80% between the experts could only be achieved within a spread of two T-types. The conclusion was that the visual classifications depended on the colour, size and quality of the image used, and that artificial neural networks could be developed to agree to almost the same degree as any pair of expert classifiers. This approach was implemented on the SDSS sample by Ball et al. (2004) with the same basic conclusion as Lahav et al. (1995), i.e., that a neural network could reproduce visual morphologies within about 1 T-type.

An alternative approach to developing methods to replicate human classification is to design computational algorithms that attempt to capture the same information. Examples of this approach include the CAS (concentration, asymmetry, clumpiness) structural system of Conselice (2006), which uses a principal-component analysis (PCA) to study the diversity of internal structures of a sample of galaxies, and the ZEST (Zurich Estimator of Structural Types) algorithm of Scarlata et al. (2007), which uses a combination of diagnostics of the galaxy shape (that can be measured directly from the galaxy images) and the more traditional Sersic index from the fit to the two-dimensional surface brightness distribution of the galaxy. Such data-oriented methods are very successful at capturing the complexity of galaxy shapes in two-dimensional images but remain hard to translate in terms of the more traditional, established morphological classes discussed above.

In recent years, there has been significant interest in the development of model–based morphologies of galaxies that use established parametric models for the light distribution of galaxies to fit to the two–dimensional images of galaxies. Such methods include GIM2D (Simard et al. 2002) and GALFIT (Peng et al. 2002) which both attempt to fit galaxy images with a combination of a disk and bulge model. These can be used to construct an objective classification scheme such as the bulge-to-disk ratio of galaxies. Unfortunately, these model-fitting techniques are computationally intense and subject to local minima as they search the high–dimensional parameter space for the best fitting model (in some cases, it can be a 12-parameter model being fit to the galaxy images).

A quicker way to solve the classification problem is to use a proxy for the galaxy class. The most common such proxy is the colour of a galaxy as most ellipticals are “red”, with their light dominated by older stars, while most spirals are “blue”, as they contain areas of active star formation which include luminous blue stars. However, relying on galaxy classification via colours as a proxy misses an important piece of the galaxy evolution story. The colour of a galaxy is driven by the stellar (and gas and dust) content of the galaxy, while the shape or morphology of a galaxy reflects its dynamical history which could be very different (and have a different timescale). Therefore, one of the central motivations for the original Galaxy Zoo project was to construct a large sample of early and late type galaxy classifications that were independent of colour.

2. GENESIS OF GALAXY ZOO

The Galaxy Zoo project was inspired by discussions of the limitations of a sample of early–type galaxies produced by Bernardi et al. (2003) from the initial Sloan Digital Sky Survey data (York et al. 2000). Bernardi et al. (2003) had used a PCA-based classification to select “passive” galaxies based on the spectra of SDSS galaxies. Although this classification scheme was fast, and easy to implement, it probably excluded early–type galaxies that had signatures of on–going star formation. It was therefore realised that to find such objects would require a sample of early–type galaxies based solely on their morphological visual appearance, without the use of spectral or colour information, i.e., that could include normal, passive “red” early–types, as well as the possibility of “bluer” star-forming early–types. Kevin Schawinski, as part of his PhD thesis work at Oxford University, under the supervision of Daniel Thomas, took on the task to build such a complete sample of early–type galaxies based solely on their visual appearance and started by inspecting 50,000 SDSS galaxies to create the MORephologically Selected Ellipticals in SDSS (MOSES) sample; an order of magnitude more than any visually inspected sample created to that point. The MOSES sample has resulted in a number of interesting results (e.g. Schawinski et al. 2007a, 2009b; Thomas et al. 2010) and in particular shows that there is a significant fraction of early–type galaxies that show recent star–formation activity.

The experience with MOSES proved the need for in-
dependent morphological classifications for galaxies, while also demonstrating that scaling the MOSES methodology to all SDSS galaxies was unfeasible for a small number of researchers to manage. At this point, Kevin Schawinski and Chris Lintott (a researcher at Oxford also involved in MOSES) became motivated to find a way to visually classify all SDSS galaxies in a reasonable amount of time, thus creating the initial "Galaxy Zoo" concept. They concluded that the only reasonable way to approach this problem was to "outsource" the visual inspection task and put it on the internet inviting volunteers to participate. At the time, the Stardust@Home project was using the internet to recruit volunteers to identify tracks made by interstellar dust in samples that were flown on NASA's Stardust sample-return mission to Comet Wild-2 (Westphal et al. 2006). Stardust@Home had ∼ 20,000 volunteers, and by extrapolation, Lintott and Schawinski figured that if even one quarter of 20,000 volunteers did one galaxy classification per day, the full SDSS Main Galaxy Sample (approximately a million galaxies) could have secure galaxy classifications in three years (assuming each galaxy was visually inspected five times each).

At the same time, another researcher at Oxford, Kate Land was planning a similar interface to classify, and characterise the sense of rotation of spiral galaxies. She was interested in an article that suggested there was a correlation between the "handedness" of spiral arms in the SDSS disk galaxies and their position on the sky, i.e., that the direction of the rotation of disk galaxies did not appear to be random (Longo 2007). Land had planned to build an interface on a laptop computer and then place it in the canteen of the Oxford Physics Department, hoping to enlist the help of her fellow scientists. However after a fortuitous meeting of the two groups, it became clear that the projects could be merged into a single interface addressing both questions.

Phil Murray and Dan Andreescu of Fingerprint Digital Media were recruited to design the Galaxy Zoo website and the initial success of Galaxy Zoo can probably be credited to the visual appeal and ease-of-use of the interface design, combined with a relatively easy classification scheme. The user was asked if the galaxy image they saw was "Spiral" or "Elliptical", followed by the classification of the apparent spin direction of the spiral arms (clockwise or anticlockwise). Another key factor was that people could get started right away after a relatively short tutorial. Once a user had passed the tutorial, they were free to classify as many galaxies as they wished and could login and out of their account as they wished. The original Galaxy Zoo team along with Land, Lintott and Schawinski included experts from the SDSS (Alex Szalay, Bob Nichol, Steven Bamford, Anze Slozar) and the MOSES team (Daniel Thomas), as well as experts in astronomical outreach (Jordan Raddick) and data archives (Jan van den Berg).

Galaxy Zoo was launched on July 11, 2007 and introduced in a BBC online article that same day. In the first three hours after launch, classifications were coming in at such a high rate that the data servers located at Johns Hopkins University hosting the site and SDSS images were unable to meet the demand. Fortunately, additional capacity was brought online quickly and, within twelve hours of the launch, the Galaxy Zoo site was receiving 20,000 classification per hour. After forty hours, the classification rate had increased to 60,000 per hour. After ten days, the public had submitted ∼ 8 million classifications. By April 2008, when the Galaxy Zoo team submitted their first paper (Lintott et al. 2008), over 100,000 volunteers had classified each of the ∼ 900,000 SDSS galaxy images an average of 38 times.

One of the unforeseen consequences of the Galaxy Zoo launch was the avalanche of email the team received from the public. Within two weeks, the original Galaxy Zoo team was swamped with requests for information and queries, and several additional people were recruited to help manage these requests. This need to communicate inspired the creation of a Galaxy Zoo internet forum which encouraged the Galaxy Zoo users to communicate with each other (overseen by the Galaxy Zoo team). This allowed many of the basic queries from the public to be answered by other members of the public more experienced with Galaxy Zoo, and also allowed the volunteers (who named themselves "Zooites") to share their thoughts and ideas with each other. Once the forum was established, several members of the public ("citizen scientists") quickly volunteered to moderate the forum and began to generate a variety of discussion threads which included basic help with understanding astronomy and Galaxy Zoo, and a repository for "weird and wonderful" images people found.

In addition to the forum, in December 2007 the team began to communicate with the volunteers through a series of blog messages about the progress of the project and science.5

3. Galaxy zoo 1

As described above, the first phase of Galaxy Zoo (now known as "Galaxy Zoo 1" or GZ1) asked volunteers to provide only basic morphological information on each galaxy. They were asked to identify if a galaxy was "spiral", "elliptical", "a merger" or "star/don't know" and additionally split the spiral category into "clockwise", "anticlockwise" and "edge-on/don't know". Galaxies for the GZ1 project were drawn from the Main Galaxy Sample of the sixth SDSS Data Release (Strauss et al. 2002) and comprised all extended objects in the survey that were brighter than a Petrosian magnitude of r < 17.77 mag. All objects were included, whether or not they had an SDSS spectrum, giving a total of 893,212 images.

3.1. From clicks to classifications

The Galaxy Zoo project was extremely successful in recruiting volunteer classifiers thus providing each galaxy in the sample with multiple independent classifications; GZ1 has a mean of 38 classifications per galaxy, with at least 20 classifications for all galaxy. Most previous morphological classifications had been done by single experts (or small groups of experts) agreeing on a single answer, but in Galaxy Zoo the situation was more like a "vote" on the galaxy classification. Going from these votes, or "clicks", to classifications can be done in several ways.

The first step in processing the user-generated data was to "clean" them by removing the tiny fraction of potentially malicious users, and any chance multiple classifications of a single galaxy by a given classifier. Next, there was a decision about how much weight each vote should have. The simplest choice is to give all classifiers equal weight. This gives a distribution of classifications for a galaxy which encodes information about the most likely classification as well as some

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5 http://stardustathome.ssl.berkeley.edu/

6 Scientists seek galaxy hunt help, by Christine McGuorty (http://news.bbc.co.uk/1/hi/sci/tech/6289474.stm)

7 http://blogs.zooniverse.org/galaxyzoo/
measure of how certain that is (in the spread of classifications).

In GZ1 a weighting scheme was also explored which weighted users based on how well they agreed with the majority (in practice this was applied iteratively). This was an attempt to give more weight to “better” classifiers, where “better” was defined as agreeing with the majority. These “weighted” classifications for the most part were similar to unweighted classifications.

3.1.1. Classification Biases

Several bias studies were run in the original GZ1 to test the effect of the interface and types of images shown to the volunteers on the classifications which were entered. The two main goals of the bias studies were to: (1) test the effect of using colour images for the classifications, and (2) test if users could reliably identify the sense of the spiral arm winding. To achieve this, a small number of monochrome and mirrored images were added to the GZ1 sample and the clicks on these images were compared to the original, unperturbed images.

Interestingly, a change in the behaviour of the volunteer classifiers was witnessed during these bias testing exercises, in the sense that users appeared to be more careful in their classifications during bias testing periods. Therefore, only clicks collected on the original images at the same time as the tests were being carried out could be used for the comparison between classifications. The results of the monochrome bias test showed that there were only small differences in the galaxy classifications between colour and black–and–white images. Users were slightly more likely to classify objects as “elliptical” in monochrome images; 56% of the votes went to ellipticals in the monochrome images compared to 55% in the original colour SDSS images.

The results of the mirror image bias testing are discussed extensively in Land et al. (2008). They showed a significant bias in favour of anti-clockwise direction arms (in both the original and mirrored images). The interpretation of this bias could be due to psychological effects (possibly related to the preference for right handedness amongst the population), or possibly site design (it being easier to click the anti-clockwise button for example). However, once this bias was corrected for, the data could still be used (see below).

Finally, another source of bias in the GZ classifications has to do with the distance to the observed galaxies. We expect that at some distance, features become harder to resolve, and more galaxies will be classified as ellipticals. This effect was indeed found in the GZ1 sample by Bamford et al. (2009) where a correction was derived as a function of redshift and galaxy luminosity. The conclusion was that the GZ1 classifications are reliable, and the bias correction is small, for redshifts below $z < 0.08$, but at higher redshifts there is a strong trend for galaxies to be classified preferentially as elliptical.

3.1.2. Comparison with Other Classifications

In Lintott et al. (2008), the GZ1 classifications were compared against three sets of independent galaxy classifications. These included early–type galaxies in the MOSES sample (Schawinski et al. 2007b), a set of 2275 SDSS galaxies of all galaxy types classified by Fukugita et al. (2007), and the sample of 2834 visually identified SDSS spiral galaxies from Longo (2007). In all cases, GZ1 classifications were found to agree remarkably well (better than 90% of the time in most cases), and the conclusion was that using data from volun-

3.2. Science Results from Galaxy Zoo 1

Classifications from GZ1 have been used for a wide range of galaxy evolution studies. A full list of the peer-reviewed papers coming from within the Galaxy Zoo 1 team is provided in Table 1. We review some of these science results here and stress that the data from GZ1 is now publicly available [Lintott et al. 2011] and being used by several scientists beyond the original GZ1 team. For example, Galaxy Zoo 1 was used to remove late-type contaminants from the study of Trujillo, Ferreras, and de la Rosa (2011), and was compared against a new method for automated classification in Huertas-Company et al. (2011). Moreover, the Galaxy Zoo 1 classifications have now been included in the Eighth Data Release of the SDSS (see Aihara et al. 2011) and can be electronically accessed alongside other SDSS galaxy parameters in their Catalog Archive Server (CAS).

3.2.1. Colour and Morphology

The greatest legacy from GZ1 has been the decoupling of colour and morphology with high statistical significance. We have demonstrated that 80% of galaxies follow the expected correlations between colour and morphology, i.e., either “red” early-type galaxies or “blue” spiral galaxies. Therefore, for a majority of galaxies, colour can be used as a crude proxy for morphology. However, GZ1 also shows that there is a significant numbers of red (passive) spiral galaxies and blue early–type galaxies. These interesting sub-populations of galaxies have been explored in a number of GZ papers (see Table 1).

This disentangling of morphology and colour has been used to study the separate dependences of the properties on environment and provide evidence that the transformation of galaxies from “blue” to “red” proceeds faster than the transformation from spiral to early–type (see Bamford et al. 2009 and Skibba et al. 2009 which use different methods to quantify this effect). The properties of the “blue” early–type galaxies in Galaxy Zoo have been studied by Schawinski et al. (2009a) and “red” (passive) spirals has been explored further by Masters et al. (2010a,b).

3.2.2. Spiral Arm Directions

The clockwise/anti-clockwise classifications of the spiral galaxies have been used to show that (as expected from the cosmological principle) there is no evidence for a preferred rotation direction in the universe, but that humans preferentially classify spiral galaxies as anti-clockwise (Land et al. 2008); and hint at a local correlation of galaxy spins at distances less than $\sim 0.5$ Mpc - the first experimental evidence for chiral correlation of spins (Slosar et al. 2009). Intriguingly there are also hints of a correlation between star formation history and spin alignments (Jimenez et al. 2010).

3.2.3. Merging Galaxies

The sample of merging galaxies has been used to show that the local fraction of mergers is about 1-3% and to study the global properties of merging galaxies (Darg et al. 2010a,b).
Multi-mergers (where more than two galaxies are merging at once) - which are much rarer than binary mergers have also recently been studied (Darg et al. 2011).

3.2.4. Active Galaxies

The GZ1 classifications also revealed interesting correlations between galaxy morphology and black hole growth. By splitting both the normal galaxy population and the active galaxy population by morphology, two fundamentally different modes of black hole feeding and feedback in early- and late-type galaxies were found (Schawinski et al. 2010b). Early-type active galactic nuclei (AGN) host galaxies are systematically lower mass and bluer than the general early-type population. Black hole growth is concentrated strongly in the "green valley" between the blue cloud and the low-mass end of the red sequence. These early-type AGN host galaxies furthermore feature strong post-starburst stellar populations (Schawinski et al. 2007b) and thus are migrating from the blue cloud to passive evolution at the low mass end of the red sequence - they are thus building up the red sequence today.

Late-type AGN host galaxies dominate by number (up to 90% if "indeterminate" are included) and reside predominantly in massive host galaxies with no indications of recent suppression of star formation. Black hole growth in these disk-dominated galaxies is likely stochastic and has no significant connection to the evolutionary trajectory of the host galaxy. Intriguingly, the Milky Way galaxy resides in the locus of mass and colour where black hole growth is most likely, potentially making the Milky Way and Sagittarius A* a prototype for this "secular" mode of black hole feeding in late-type galaxies.

3.2.5. Rare and Unusual Objects

GZ1 has brought to light several rare classes of object. “Hanny’s Voorwerp” is perhaps the most famous of such objects and many are familiar with the story of the Dutch school teacher Hanny, who first noted this object (she was not the first volunteer to see it, but the first to ask about it) which is now memorialized in a Comic Book10. The Voorwerp is an unusual emission line nebula neighbouring the spiral galaxy M81 which allows fainter structures in these galaxies to be visible.

Another unusual class of objects discovered by the Galaxy Zoo volunteers are the “Green Peas”. The properties of these emission-line galaxies, which appear green in the SDSS composite gri colour images because of their strong [OIII] emission, are studied in detail in Cardamone et al. (2009).

4. EVOLUTION OF GALAXY ZOO

4.1. Galaxy Zoo 2 and Hubble Zoo

As the original Galaxy Zoo was the first time such a project had been attempted, the Galaxy Zoo team was cautious with their classification scheme, only asking for simple information about the appearance of the galaxies. Thanks to the overwhelming response, and prompted by requests from the volunteers who wanted to provide more detailed classifications, the team realized they could harvest much more information from the SDSS images than in GZ1. Therefore, Galaxy Zoo 2 (GZ2) was designed around asking more detailed questions about the ~ 250,000 brightest SDSS galaxies from the original GZ1 sample of galaxies.11 Once again, the response was tremendous and in the fourteen months the site was live, Galaxy Zoo 2 users provided over 60 million classifications. Along the way, deeper SDSS images were added for a subset of GZ2 galaxies, taken from a patch of the sky known as "Stripe 82" which allows fainter structures in these galaxies to be visible.

The first science results from GZ2 classifications are now appearing. In [Masters et al., 2011], we showed that the fraction of barred disk galaxies (as compared to unbarred galaxies) depends on other galaxy properties, especially the overall colour of the galaxy and the size of the central bulge. As a satellite project, Ben Hoyle at Portsmouth University developed an additional web interface using Google Maps technologies to allow GZ2 volunteers to draw the shapes and sizes of bars on GZ2-selected disk galaxies (Hoyle et al. 2011). From September 2009 to January 2010, he received 16,551 bar drawings for 8180 galaxies, making it by far the largest sample of disk galaxies with known bar lengths; again demonstrating the attraction of Galaxy Zoo even for such a complex task. These studies combined show the strong connection between the bar of a disk galaxy and its overall colour, i.e. disk galaxies with long bars also exhibit prominent bulges and have redder colours than galaxies with smaller bars.

After Galaxy Zoo 2, the team launched “Hubble Zoo”. To really understand galaxy evolution, and to get a sense of how

10 see http://hannysvoorwerp.zooniverse.org/

11 The website (http://zoo2.galaxyzoo.org/) for this phase of Galaxy Zoo was designed by Phil Murray and implemented by Danny Locksmith and Arfon Smith.
The colour-morphology relation might change over time, it is important to be able to classify morphologies for galaxies that are much further away than those classified from the SDSS. The light from these galaxies has taken much longer to get to us and hence provide images of galaxies at a much earlier epoch in the history of the universe. Such a dataset will allow us to answer questions like: Are there more blue ellipticals compared to red ellipticals earlier on in the Universe? Does the number of irregularly shaped galaxies increase as we look back further in time? To compare the results from the GZ1 and GZ2 classifications of the SDSS galaxies to galaxies at an earlier epoch, the latest incarnation of Galaxy Zoo is using data from the Hubble Space Telescope (HST) which goes deeper than ever before, e.g., HST COSMOS (Cosmic Evolution Survey) has over two million galaxies that cover 75% of the age of the universe (Scoville et al. 2007). Hubble Zoo is currently undergoing classification using HST data from GEMS (Rix et al. 2004), GOODS (Giavalisco et al. 2004), AEGIS (Davis et al. 2007) and COSMOS (Scoville et al. 2007). The decision tree is identical to that for GZ2 except that there is an additional branch that classifies the “clumpiness” and symmetry of each galaxy.

4.2. The Citizen Scientists - Motivation and Unexpected Outcomes

Within the first several days after launch, it was clear to the Galaxy Zoo team that they had hit a nerve with the public - classifying galaxies on Galaxy Zoo provided some sort of fulfillment for the volunteers. GZ team members suspected that the popularity of the project relied on the beauty of the images, or that the project had benefited from particularly good and lucky publicity. Already, team members were thinking of other scholarly areas where applying the method of visually inspecting data could lead to publishable results beyond what could be accomplished by application of machine algorithms. But before any such steps could be taken, it was essential to understand the motivations for volunteers participating in Galaxy Zoo. A survey of the motivations of citizen scientists involved in Galaxy Zoo is presented in Raddick et al. (2010). The results show that by far the most common motivation Galaxy Zoo volunteers cite for their involvement in the project is their desire to contribute to real scientific work.

Thus it should not have come as a surprise that many Galaxy Zoo volunteers developed their own lines of inquiry off the main task page. The Galaxy Zoo forum acted as a clearing house for volunteers to describe and discuss objects that they felt were noteworthy. Several threads were devoted to collecting objects with specific characteristics, e.g. triple mergers, or overlapping galaxies, or small, round, green galaxies dubbed “Peas”. These three examples have all resulted in scientific papers (Darg et al. 2011) Keel et al. 2011). Cardamone et al. 2009), respectively.

But one of the critical aspects enabling the development of collections and further inquiry into an object’s characteristics was the link from the main task page for each object to the SDSS SkyServer Object Explorer page. This page aggregated information about the galaxy including the image and accompanying spectrum as well as information about its magnitude, redshift, cross-identifications in other wavelengths and a host of links to more information such as NASA’s Extragalactic Database.

That Galaxy Zoo volunteers began to notice that the “Peas” all had extraordinarily high fluxes in the [OIII] emission line. Eventually over 250 of these objects were found while volunteers taught each other through the forum what the characteristics of a “pea” were and began to trade literature searches on what [OIII] meant and possible interpretations of these galaxies. After several months collecting and interpreting on their own, a graduate student from Yale, Carie Cardamone was assigned to moderate the “Peas” forum, working with the volunteers while she developed the full analysis of these rare dwarf galaxies with extremely high star formation rates (which was published as Cardamone et al. 2009).

The story of the Galaxy Zoo “Peas” inspired the team to ensure that future projects provide links to supporting information and analysis tools related to the objects shown in the primary task. This is to enable the users to conduct their own research and allows for users to learn the process of research aided by peer-mentoring.

The experience with the Galaxy Zoo forums and blogs shows that the citizen scientist volunteers wanted to do much more than classify objects. They built a community of the volunteers, by the volunteers and for the volunteers. Indeed, Galaxy Zoo belonged to the volunteers - it was their time just as much as it was the scientists time spent working on the project. The team understood this important fact and made it a point of principle to keep the volunteers informed about various aspects of the project from the technical to the social and scientific. Moreover, the team realised early on that they must respect the time and commitment of the volunteers, and should only harvest classifications for as long as they were scientifically useful.

In fact the volunteers have set up several projects of their own using Galaxy Zoo infrastructure or methods. The largest example of such a project is probably the “Irregulars” project. Initiated by Galaxy Zoo volunteers Richard Proctor (“Waveney”) and Julia Wilkinson (“Jules”) on a forum thread, the aim of this project was initially to collect a sample of irregular galaxies, i.e. galaxies that did not fit in to the classification scheme at all. This project now uses a self-built web interface (similar in style to Galaxy Zoo) to ask for classifications of the objects and has inspired several volunteer led research papers. Richard Proctor has recently applied to do a part-time PhD at the Open University using the data collected in this project.

The Galaxy Zoo forum has been a scientific gold mine on several occasions. Examples of science results coming directly from the forum include the discovery of the Voorwerp (Lintott et al. 2009), targeted and serendipitous searches for smaller versions of the Voorwerp (“voorwerpjes” Chojnowski & Keel 2011) Gagne et al. 2011), the Peas (Cardamone et al. 2009), overlaps (Keel et al. 2011), ring galaxies, etc. The depth of interest shown by some of the volunteers is extraordinary. Volunteer, Richard Proctor (“Waveney”) has set up web forms for several searches and sample evaluations (including the “Irregulars” project mentioned above). Massimo Mezzoprete (“Half65”) was so interested in the overlapping-galaxy search (Keel et al. 2011) that he learned SQL and perl, creating a tool that he could point to a forum thread and have it parse for either kind of unique SDSS Object ID, then query the Catalog Archive Server and create a PDF with a page of
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finding chart, photometry and positional data for each object. (Mezzoprete is a co-author on the first overlapping-galaxy paper). These forum results clearly show that through the Galaxy Zoo project, citizen scientists have become research collaborators.

5. THE ZOONIVERSE

The extension of the Galaxy Zoo idea to other scientific domains is obvious in our data-rich world, especially given the desire of the public to be involved in scientific investigations of these data. Researchers across a diverse range of academic fields face the common problem of developing new strategies and modes of computational thinking needed to transform this data flow into knowledge. With the current moderate-sized databases (terabytes), citizen science methods like Galaxy Zoo can replace some aspects of machine algorithms. However, as the data deluge will only intensify in the next decades, machine algorithms must advance to meet the data processing demands, incorporating techniques based on developing areas such as computer vision. Instead of displacing the citizen science method, these new algorithms will need to be trained from, and tested by, human input (e.g. GZ1 classifications have been used for machine learning in Banerji et al. [2010]). Thus, the visual processing methods of Galaxy Zoo will become essential to fully extract information from the data.

It is tempting to think of Galaxy Zoo purely as an Education and Outreach endeavor with all its successes in garnering publicity and focus on a community of non-expert volunteers. And with that temptation, one might imagine applying the Galaxy Zoo method to an indiscriminate array of projects with the idea that the public would be engaged in the process so it does not matter if the scientific outputs were “real” or whether the data processing could have been better accomplished through standard computational methods. What must be made clear is that Galaxy Zoo turned citizen science into a data processing method - a data reduction tool for data-intensive science which when applied correctly provides the best possible data product from a set of “raw” data. The genius in this method lies in the fact that the public actually prefer to participate in a meaningful set of tasks where they know their work is useful. Galaxy Zoo established this coupling between high-priority science output and the public engagement in science. Once it became clear that the appetite of the public for participation was considerable, these factors can then reduce the overhead on recruiting volunteers and allows for the possibility of deploying small and exploratory projects that would be prohibitive to create on their own. Building on the zoo aspect of the Galaxy Zoo brand, the “Zooniverse” became the answer to how to create a centralized portal to a universe of Zoo-like projects.

To turn the “Zooniverse” into reality, several new projects with data sets beyond the SDSS were developed. In order to help manage the Zooniverse and its expanding set of projects, in June 2009 the Citizen Science Alliance[17] was formed initially by Chris Lintott, Steven Bamford, Lucy Fortson and Arfon Smith. The Zooniverse Project[18] website was launched in December 2009.

To shift from the original Galaxy Zoo to the Zooniverse, substantial technical changes were implemented in order to produce a robust and flexible system. The most important change was the shift from hosting on a single server to hosting in the “Cloud”, i.e., making use of commercial services provided by Amazon Web Services. This technology allows new servers to be brought online in response to demand, and therefore allows the site to cope with spikes in internet traffic due to the fluctuating media coverage. The new system is built in a “Ruby on Rails” framework with a restful API layer between a thin web layer and the database. Authentication of users is carried out by an implementation of the Central Authentication Service (CAS) single sign-on solution. This technology allows volunteers to use the same account for both the forum and the main Galaxy Zoo site, as well as between different projects. The use of an API allows the Zooniverse team to support not only the main website but also iPhone and Android applications, allowing mobile users to take part in Galaxy Zoo. Early results suggest that this may be an effective way of increasing the number of classifications per user.

The Zooniverse codebase was designed with a flexible domain model and extensible reuse of code. These attributes allow features developed for new projects to be usable by all projects. The use of cloud computing services provides hosting scalability, while the virtual platform also handles content distribution and asynchronous classification processing. As of early 2011, the “Zooniverse” is running eight Zoo projects and has handled many millions of classifications by more than 250,000 users. Several different task functions have been implemented through these projects including basic decision trees, drawing shapes on images (“MoonZoo”, “Milky-Way” Project), real-time asset prioritization and alerts with the Galaxy Zoo Supernova project of Smith et al. [2011], manipulating simulated data parameters (Galaxy Zoo Mergers) and text transcription (“Old Weather”).

To aid in the development of the Zooniverse as a community of citizen scientists, and to enable users to engage in inquiry related to the data for a given Zoo, a discussion tool was recently developed to replace the forum structure used in GZ. The new discussion tool (called “Talk”) was launched with the Milky Way Project and encourages users to create collections of objects, share information and join in online discussions. Several social media features such as tagging, tag clouds, “trending” and “recent” toggles improve Talk over the older forum structure, while retaining the primary collaborative functions such as the discussion boards in Galaxy Zoo.

[17] see http://www.citizensciencealliance.org
[18] http://www.zooniverse.org
The Zooniverse team has already seen a marked increase in traffic to Talk compared to the number of users navigating to the old forum structure.

The Zooniverse team also has developed numerous education resources and continues to conduct education research into the motivations of the volunteers to contribute to tasks, how usage patterns vary over different levels of engagement with the project and whether there is any gain in understanding the process of research - just to name a few of the topics. Further description of these efforts is outside the scope of this paper.

5.1. Tasks suitable for the Zooniverse

One of the difficulties for the Zooniverse is understanding the types of tasks that are suitable for citizen scientists. The original Galaxy Zoo project primarily asked users to classify images. The interface was simple, with only a few buttons to click for every image. Some of the early success of this project might have been due to the simple requirements of this task.

The newer Galaxy Zoo 2, Hubble Zoo and Galaxy Zoo Supernova project are also based on having volunteers do classifications on images. However, these projects use a context-based decision tree to ask more detailed morphological questions about the objects, rather than just using a single classification of an object. If the galaxy was a spiral, does it have a bar at the center? How many spiral arms are visible? Although each question only has a few possible answers, the data for each object has more detail than would be possible from a single question interface.

The GZ “Mergers” project operates in a fundamentally different way than the others Zoos. Users are not asked to classify images, but rather to match simulated images to data. In some cases, none of the simulations presented are similar to the target galaxy. In other cases, there are several selections possible within the main interface. After selecting an image, users then have the option of enhancing it using a Java applet. By using two dimensional sliders, the users can generate new simulations to try to make their results match the target image more closely. The overall approach of this project has some similarities to on-line citizen science games like “Fold-It!” The primary difference is the lack of an objective score for the goodness–of–fit. In the case of mergers, we do not have such an objective fitness function, as one of the goals of the project is to create a sufficiently large sample of galaxy mergers that such a function could be derived. The users therefore have to use their best judgement to determine the goodness–of–fit.

When the GZ “Mergers” project first started, there were a large number of images that were being viewed every day. Of the images being viewed, approximately 5% were selected by the volunteers as possible matches to the target galaxy. Upon inspection, the science team found that a high fraction (up to 95%) of the simulations were not likely matches to the real galaxies, as it appeared that many simulations were inadvertently selected, or inexperienced users tried to select too many simulated galaxies as matches. To increase the fraction of good matches, the team created a second level interface called “Merger Wars”. In this interface, volunteers were given the opportunity to select the best of the simulation images by allowing the full suite of simulated images to compete with each other in one-to-one competitions, e.g., users were shown only two simulations at a time, and asked to pick the best one, and then iterate. Although some of this analysis is still underway, the science team believes that the selection rate for good matches has dramatically improved. A larger fraction of the originally selected simulations get zero votes in this second level competition.

In the Planet Hunters site, users are not looking at images, but rather are presented with time series data on the light curves of nearby stars, and are tutored on how to recognize the signature of an extrasolar planet in that data. Despite the seemingly esoteric nature of light curve data this Zooniverse project has been very successful, proving that citizen scientists are happy to deal with more complex types of data possibly because the scope for discovery is high.

In addition to classification and matching, citizen scientists are also being asked to do measurements on images. In the “Solar Storm Watch”, “Moon Zoo”, and “Milky Way” projects, volunteers use drawing tools to identify features. In the “Moon Zoo”, for example, volunteers are asked to draw circles around the rims of craters. A similar process is used to identify bubbles in the interstellar medium in the “Milky Way” project.

In some ways, these last projects require more advanced skills and more patience than just clicking through a classification tree. However, with the right interface and the right users, very good results can be obtained on these types of projects.

A key observation from all of these Zooniverse projects, and from the forums and Talk interactions, is that some of the volunteers have very advanced abilities and interests. There is a great deal of effort being dedicated to develop a suite of tools that allow these users to do additional scientific investigations on their own and, as discussed above, some of the most interesting discoveries come from the users themselves.

5.2. Data Mining the Zooniverse Results

One of the key features of the Zooniverse project is the application of machine learning (data mining) algorithms to the Zooniverse volunteer-contributed tags. These tag data themselves generate a significant volume of data (e.g., the many hundreds of millions of galaxy classifications from Galaxy Zoo). Finding correlations and trends among these user-contributed tags alongside automatically measured parameters of the same objects within the science database (e.g., the SDSS object catalog) will enable the development of improved classification and anomaly-detection algorithms for future sky surveys (such as the Large Synoptic Survey Telescope (LSST)), which will measure properties for at least 100 times more galaxies, 100 times more stars, and 100 thousand times more source observations.

For example, a preliminary study of the galaxy mergers found in the Galaxy Zoo I project was carried out (Baehr et al. 2010). It was found that certain science database parameters in the SDSS science database correlated strongly with how often Galaxy Zoo users identified an object as a merger. These database attributes included: (a) the log-likelihood that the galaxy’s surface brightness profile was fit neither by an exponential disk (the lnLExp_u attribute in the PhotoObjAll table) that is typical of spiral/disk galaxies nor by a de Vaucouleurs profile (the lnLDeV_u attribute in the PhotoObjAll table) that is typical of elliptical galaxies; (b) a gradient in the position angle of the...
isophotal major axis of the galaxy (the isoAGrad_u attribute in the PhotoObjAll table up to Data Release 7); and (c) the galaxy’s “texture” (the texture_u attribute in the PhotoObjAll table up to Data Release 7), which is essentially the RMS (root-mean-square) variation of the galaxy’s surface brightness profile relative to one of the standard galaxy profile-fitting functions. In hindsight, it could have been predicted that these parameters would be useful in distinguishing normal (undisturbed) galaxies from abnormal (merging, colliding, interacting, disturbed) galaxies. These results may now be applied to future sky surveys, to improve the automatic (machine-based) classification algorithms for colliding and merging galaxies. All of this was made possible by the fact that the galaxy classifications provided by Galaxy Zoo I participants led to the creation of the largest pure set of visually identified colliding and merging galaxies yet to be compiled for use by astronomers.

Another example of machine learning using Galaxy Zoo classifications is provided in Banerji et al. (2010) who trained a neural network on a subset of the GZ1 data; and (depending on the automatic measurements given to the algorithm) could reproduce the classifications to better than 90%. They concluded that Galaxy Zoo would provide an invaluable training set for future algorithms likely to be developed to classify the next generation of wide-field imaging surveys.

5.3. Future citizen science projects

With all the recent activities in the Zooniverse, it is important to consider the implications that citizen science has for future astronomical projects (e.g. LOFAR (Falke et al. 2007), and the Dark Energy Survey [21]). For example, we briefly consider here how volunteers might help with a project like the Large Synoptic Survey Telescope (LSST) (LSST Science Collaboration 2009), when it comes online this decade.

During the first Galaxy Zoo project, volunteers examined images of approximately one million galaxies. The storage space needed for all of these images was only a few Terabytes and therefore relatively easy to host and serve. In contrast, LSST will generate tens of Terabytes per day and over its approximate ten-year operational lifetime, it is estimated that it will generate tens of Petabytes.

Among the citizen science projects that may contribute to LSST science are those that explore the time series data from the survey. Since LSST will do repeated imaging of the sky over the 10-year project duration, each of the roughly 50 billion objects observed by LSST will have approximately 1000 separate observations. These 50 trillion time series data points will provide an enormous opportunity to discover all types of rare phenomena, rare objects, rare classes, and new objects, classes, and sub-classes.

No group of volunteers could hope to view all such data being generated from LSST. At the same time, the science team on the project will have no hope to keep up with such a data flow from the system. Obviously, automatic algorithms need to be used to triage the data and do basic classification of events. However, even with automatic classification, it is anticipated that tens of thousands (or more) anomalous events will be detected every day. Some of these might be astronomically significant (asteroids, supernovae, etc). However, many will not fall into any particular category, and in many cases, they might be some kind of noise (an airplane flying in the field of view).

The contributions of human participants may include: detection of unusual light curves in rotating asteroids; human-assisted search for best-fit models of these asteroids (including shapes, spin periods, and varying surface reflection properties); discovery of unusual variations in known variable stars; discovery of interesting objects in the environments around variable objects; discovery of associations among multiple variable and/or moving objects in a field; and more. This is especially important for the nightly event stream – perhaps 100,000 new events will be detected each and every night for 10 years. There are not enough observing facilities or professional astronomers (or graduate students) in the world to follow up on each of these events. Engaging a large cohort of willing participants to examine these events will contribute significantly to the scientific discovery efficiency and effectiveness of the LSST survey: citizen scientists may explore this massive event stream for novel and interesting features, thereby characterizing the behavior of each such object. The creation of a “characterization database” of time-varying objects (from which astronomers may query, search, and retrieve events based upon prescribed characteristic light curve behaviors) may prove to be one of the most significant contributions of citizen scientists to the LSST project – i.e., the development of a major externally joined database component of the LSST science data collection.

Something like this approach was effectively used with the detection of the “Peas” described above (Section 1.2.4.4), i.e., once this class of objects was discovered, and determined to be interesting, a computer algorithm was developed to find them (Cardamone et al. 2009). By finding new classes of data, volunteers can make major contributions to science that would not be possible without their help. The Galaxy Zoo Supernova project also uses a similar methodology (Smith et al. 2011). During an observing run, the science team receives tens of thousands of possible supernova candidates, and automatic algorithms are used to reduce this to a few hundred events a day that are likely supernovae. With the help of citizen scientists, these candidate supernovae are visually checked and thus confirmed for follow-up observations in real-time.

In summary, as the data rates increase, and we become further dependent on automatic classification algorithms, citizen scientists can play a crucial role in reviewing subsets of the data and identifying anomalies. The algorithms can then be adapted by the science teams to increase their success rate (based on the visual checks). The two methodologies will need to work in tandem and the process will likely be iterative.

6. GALAXY ZOO IN THE CONTEXT OF OTHER CITIZEN SCIENCE PROJECTS

Galaxy Zoo is certainly not the only citizen science project. As mentioned in the beginning of this chapter, one of the inspirations for Galaxy Zoo was the Stardust@Home project (Westphal et al. 2006). This was one of the few projects at a time where volunteers were asked to participate in the data analysis of a project rather than the data collection phase of a project. Many of the historically significant citizen science projects, such as the Audubon Society’s Christmas Bird Count program (started in 1900) and the American Association of Variable Star Observers variable star observations project (starting in 1911), were based on data collection. With the advent of the internet as a distribution system, citizen science projects could move into work on data analysis. Here we make a distinction between distributed analysis projects
and distributed computation projects such as SETI@Home\footnote{http://setiathome.berkeley.edu/index.php} which utilizes the computational power of over a million idle computers belonging to volunteers to process radio data looking for signals that could indicate extra-terrestrial intelligence. Distributed analysis projects require the brain - or the “wetware” - of the volunteer to be engaged, not just their computer. One of the earliest distributed data analysis projects (dating from 2001) was Clickworkers which asked the public to count the number of craters on maps of the Martian surface returned by the Mars Orbiter Camera (MOC). While the project was successful in recruiting sufficient volunteers to identify over 800,000 MOC craters\citep{Gulick et al. 2010}, there are few scientific results published as of yet on this body of work. Clickworkers has morphed into a project with a more game–like interface\footnote{http://fold.it/portal/} where the public are currently asked to “tag” surface features on images from the Mars Rovers, Spirit and Opportunity. Another project with a game–like interface is FoldIt!\footnote{http://www.cocorahs.org/} which asks the public to help solve protein folding “puzzles”. Both the new Clickworkers and the FoldIt! projects require the user to download an application. In the context of distributed data analysis projects, Galaxy Zoo (and its successor projects in the Zooinverse) is quite probably the largest both in terms of number of registered volunteers world–wide as well as number of peer–reviewed papers published based on data processed by volunteers.

There are many excellent citizen science projects in ecology, animal studies and other disciplines where the distributed nature of data collection is critical to the success of the project. For example Cornell University’s Lab of Ornithology FeederWatch Project\footnote{http://www.birds.cornell.edu/pfw/} asks volunteers to enter counts of bird species into an online form to track winter bird populations, or the CoCoRaHS Network (Community Collaborative Rain, Hail and Snow Network)\footnote{http://www.cocorahs.org/} has thousands of volunteers across all fifty of the United States who have installed sensors outside their homes and record amounts of rain, snow and hail. Thus, one potential trend in citizen science will then be projects that link the distributed data collection and distributed data analysis aspects of their work.

7. CONCLUSIONS

In this chapter we have presented a brief overview of the Galaxy Zoo and Zooinverse projects. We gave a short discussion of the history and motivation for the original Galaxy Zoo, as well as the motivations to extend it to “Galaxy Zoo 2”, “Hubble Zoo” and an entire “Zooinverse” of citizen science projects. We have described the highlights of the many scientific results that have already come from Galaxy Zoo.

We go on to discuss what makes a good citizen science project, and why we think Galaxy Zoo was so successful. We describe the importance of having a central portal, the Zooinverse, as a gateway to citizen science projects across multiple disciplines. We then consider likely future applications of community–based science in the coming data–rich era. Finally, to provide a context for the importance of the Galaxy Zoo project, we present a short description of various other citizen science projects and modalities.

Galaxy Zoo and the many Zooinverse projects would not have been possible without the participation of over 400,000 volunteers who have registered with the Zooinverse. The contributions of volunteers to Galaxy Zoo are individually acknowledged at http://www.galaxyzoo.org/Volunteers.aspx, and volunteers who classified in Galaxy Zoo 2 (and wished to be acknowledged) are listed at http://zoo2.galaxyzoo.org/authors. The work described in this paper is funded in part by The Leverhulme Trust (UK), the National Science Foundation and the National Aeronautics and Space Administration (US).

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