1a: The Moon Zoo website and graphical interface for the crater identification and measurement task. A small portion of the lunar surface is shown in the GUI with an indication of lighting conditions (what a shadow will look like) provided in the bottom left-hand corner. A crater has been identified in the lunar image and its size has been adjusted to fit over the crater rim. On the right are the task options, including crater identification (top cross), feature identification, and options to indicate if a crater is full of boulders or not.

1b: The Moon Zoo website and graphical interface for the boulder wars task. Users select the image that has the greatest number of boulders. They can also identify interesting features in the image by selecting the "!" tool on the right.

Moon Zoo: citizen scien

Katherine Joy, Ian Crawford, Peter Grindrod, Chris Lintott, Steven Bamford, Arfon Smith, Anthony Cook and the Moon Zoo Team describe how citizen scientists can get involved and explore the Moon online.

Moon Zoo is an online lunar citizen science project designed to address key questions in lunar and planetary science. It is one of several initiatives developed by the Citizen Science Alliance in a collection of online citizen science projects known as the Zooniverse. These projects are inspired by the highly successful Galaxy Zoo project, which harnesses the power of internet users (i.e. crowdsourcing) to classify galaxies in support of astrophysics research (Lintott *et al.* 2008).

Launched in May 2010, Moon Zoo sets registered users the task of identifying, classifying and measuring feature shapes on the surface of the Moon using specially designed graphical interfaces (figure 1). Moon Zoo uses the Planetary Data System high spatial resolution images (with associated metadata) from NASA's Lunar Reconnaissance Orbiter (Chin *et al.* 2007) Narrow Angle Camera (LROC NAC) instrument (Robinson *et al.* 2010), which has been orbiting the Moon since June 2009. These spectacular images are providing new insights into the diverse morphology and geological make-up of the lunar surface. The unprecedented high resolution of the NAC images means that it is even possible to spot tyre-tracks left by the Apollo lunar rovers and see actual boulders that were photographed (figure 2a) and sampled by the astronauts! Hundreds of thousands of LROC NAC images have been made publicly available, and one of the main advantages of Moon Zoo is the ability to analyse and classify such large amounts of data with multiple independent observations.

The Moon Zoo project

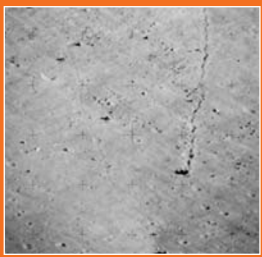
The goal of Moon Zoo, like all other citizen science projects, is to deliver high-quality science while prompting a wider understanding of that science and of the data-collecting process. Moon Zoo also provides a wide range of education material, sourced from learning sites across the internet, to allow users to find out more about the Moon and planetary processes. Users are encouraged to join the Moon Zoo Forum where they can discuss interesting discoveries or seek guidance about the project. A discovery is highlighted each week in the Moon Zoo Image of the Week announcement. A blog site provides more in-depth explanations about lunar geology and exploration so that users can enhance their engagement with the project. Additionally, educational research is being completed to identify trends in the classification habits and site usage of Moon Zoo users over time, to measure understanding of lunar concepts, and to determine what motivates users to be part of this project.

Scientific objectives

Moon Zoo tasks have been designed to address outstanding lunar science questions (NRC 2007) and to help in planning efforts for future lunar exploration. The objectives include:

- **Statistical studies of small impact craters.** This involves cataloguing the location and dimensions of small (diameters between 10 and 100s of metres) impact craters on the Moon. A database of crater size, shape and distribution can be employed to address a range of lunar and planetary science issues. For example, small crater populations can be used to help determine the "ages" of lunar geological units. This relative age dating methodology is based upon models of crater size–frequency distributions (CSFD: Hartmann 1977, Wilhelms *et al.* 1978, Moore *et al.* 1980, Neukum *et al.* 2001, Ivanov *et al.* 2000, Stöffler *et al.* 2006 and references therein) that are calibrated at the Apollo and Luna landing sites where surface ages of geological units are inferred from returned-sample radiometric ages. Moon Zoo crater counts will help to constrain the crater production function of small

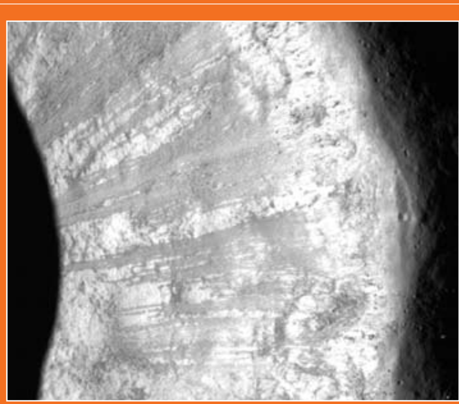
EXAMPLES OF MORPHOLOGICALLY INTERESTING LUNAR SURFACE FEATURES FOUND BY MOON ZOO USERS



2a (Top): A large track left by a boulder that rolled down a slope (the boulder is just out of shot at the bottom of this frame). Moon Zoo Forum users Caro and Jules posted this image in the Moon Zoo Forum, and it featured as the site's Image of the Week on 21 June 2010. (From LROC NAC image M116113215R). (Bottom): The photograph is the same boulder track (and dark boulder) photographed by astronaut Gene Cernan in the Taurus Littrow valley visited by the Apollo 17 mission. (NASA image AS17-144-21991)

2b: This crater chainlet was referred to by Forum users as Caro's Tadpole. It has been shown in the lab (Gault and Wedekind 1978) that, during an oblique impact, the projectile can break up and fragments thrown down-range (here towards the lower left) of the primary crater (top right) cause a secondary crater chain. (From LROC NAC image M106726943R)

2c: This bench-crater is close to the Apollo 12 landing site. The regolith here is relatively thin, and is underlain by a more consolidated lava flow. The impact has punched through the regolith and into the harder rock, excavating large blocks that have covered the surrounding surface. The crater must be relatively fresh (<1 billion years or so) to be so well preserved. (From LROC NAC image M114104917L)



2d: This close-up of Marius D crater featured as Image of the Week on 8 November 2010. The impact crater floor (left) is in shadow, and the target surface (right) is very dark. The crater wall stands out for its high albedo, and is covered by a series of small debris flows and gullies that were created when material from the top of the crater wall fell under gravity towards the crater floor (right to left). Boulders and different grain-size material can be seen in and around the debris flows. (From LROC NAC image M102265088L)

ce in lunar exploration

impact craters in a range of geologic terrains. We also intend to provide new statistically reliable estimates of small-crater populations at the Apollo and Luna landing sites to help validate crater size–frequency distribution models and to better constrain our understanding of the age of the lunar surface. As the dimensions of a given crater are assessed by several users in Moon Zoo, the statistical variability of these ellipse/circle locations can be analysed and exploited to determine the state of crater degradation, which provides another independent estimate of surface age. This crater degradation approach is of particular interest for determining the ages of small geologic units where there are too few craters to perform significant cumulative crater counts (e.g. Stöffler *et al.* 2006).

• **Constraining the thickness and variability of the lunar regolith.** Regolith depths on the Moon are only accurately constrained at the six Apollo landing sites where *in situ* seismic experiments were set up. Small-crater populations and identification of craters with many ejected blocks and boulders (Wilcox *et al.* 2005) can also be used to identify discontinuity in regolith layers (e.g. transition from upper regolith to underlying bedrock unit or more consolidated mega-regolith horizon). Understanding the thickness of the lunar regolith helps to provide another independent surface-age estimate. Conversely, measuring the regolith thickness on units with well-determined ages will help to temporally constrain regolith accumulation rates.

• **Map the distribution of boulders on the lunar surface.** Identification of boulders in images can be used to produce relative boulder-density maps. These data can help to identify the locations of unmodified blocky ejecta blankets and rays and can be compared to similar rock abundance maps being produced by the LRO Diviner radiometer instrument (Bandfield *et al.* 2010, Ghent *et al.* 2010) and terrestrial radar observations of the lunar regolith (Ghent *et al.* 2005, 2010). Such datasets can be used as hazard maps to help identify suitable landing sites for future missions to the Moon.

• **Identify and catalogue unusual geological features.** Morphologically and geologically interesting lunar features can provide insights into the geological evolution of the Moon. The morphological variation of impact craters can indicate local geologic variability. For example, craters with dark halos are sometimes seen on the lunar surface where the projectile has punched through an overlying high-albedo layer, excavated underlying lava flows (known as cryptomaria), and scattered this darker material over the surrounding brighter materials (Hawke *et al.* 1985, 2005, Antonenko *et al.* 1995, Campbell and Hawke 2005). Mapping these types of impact craters can therefore constrain the extent of cryptomaria deposits on the Moon. Identifying craters with concentric benches/central mounds/flat-bottoms (figure 2c), and measuring their size, may provide an indication of local stratigraphic variation and regolith depth (Quaide and Oberbeck 1963, Oberbeck 2008). Identification of small (<2 km diameter) very fresh impact craters that preserve a record of their ejecta blanket is also of scientific interest as they are the most likely settings from which lunar meteorites (as found on Earth) have been ejected (Warren 1994). Therefore, we foresee that a database of small, fresh impact craters will aid searches for the provenance of these important samples.

Linear features on the Moon indicate a wide range of geological processes from lava channels and tectonic movements, to mass wasting gullies and debris flows (see figure 2d and Bart 2007). Identification of linear chains of impact craters (figure 2b) will help to identify locations of crater rays and secondary impact crater events. Mapping the location of boulder tracks (figure 2a) on the lunar surface is of interest to future mission planning exploration initiatives as detailed geological field excursions could be developed to visit boulders sourced from inaccessible or distal rock outcrops.

In addition, the experience of Galaxy Zoo leads us to expect that important discoveries of interesting lunar surface features are likely to be made serendipitously.

• **Other scientific benefits.** Moon Zoo crater survey results can be compared with automatic computer-based methods of crater counting, for example, to assess the capabilities of the latter against human efforts (e.g. Urbach and Stepinski 2006). This will make a significant contribution to assessing the reliability of the computer algorithms, which are likely to play an increasingly important role in planetary science but which can only be tested against very large datasets such as that being amassed by Moon Zoo.

We envisage, and hope, that members of the wider lunar science community will be able to use Moon Zoo lunar feature catalogues to aid their own planetary science research objectives.

Moon Zoo interface and tasks

Moon Zoo uses two graphical user interfaces (GUIs) to enable users to collect data to address these scientific goals. A small portion of an LROC NAC image is presented to the user in each interface (figure 1), with overlap between different image frames to ensure total NAC frame coverage. Several tasks are presented in each interface, and it is up to the user to decide how many tasks to perform when they are reviewing an image. The images include a range of different zoom levels and sizes so that users study the lunar surface at scales from the metre to the kilometre, in order to map a range of sizes of craters and features. However, we do not provide a scale on the images presented, so that results are not biased towards identifying a particular type of lunar feature.

The first Moon Zoo GUI is shown in figure 1a. This interface allows users to identify and determine the dimension of impact craters on the lunar surface to help provide a statistical analysis of lunar crater populations. A drop tool is used to identify the location of a crater, and the user can manipulate the tool's size to fit to the crater rim dimensions (an example is shown in figure 1a and a full tutorial is available on the website). Craters can be identified down to an image size of 20 pixels, which equates to a crater size of about 10 m in the highest spatial resolution LROC NAC images. To assess regolith variability, users can identify impact craters that are surrounded by, or contain, lots of blocks and boulders (e.g. see figure 2c). To address the feature-cataloguing science goal, users are provided with an option to flag any "interesting" morphological features in the image, and can select the type of feature they have spotted by using a drop-down option list. Training tutorials and guides are also provided to teach users how to identify features of interest. It is often the case that users will flag unique finds or unusual features in the Moon Zoo Forum, so that discoveries can be discussed by a wide range of users. When a user has finished the tasks and submits their work, classification details are written to the results database.

The second Moon Zoo GUI is shown in figure 1b. In this interface uses are asked to study two side-by-side images of the Moon (taken at the same spatial resolution) and to identify which one has the most boulders in view (including an option to select if neither area has any boulders). Again, users can flag any "interesting" morphological features in the image, if they spot any unusual landforms while completing this task.

The Galaxy Zoo project uses statistical analysis to study the quality of user classifications (i.e. how often they get the "correct" answer compared to an expert classification; how varied the classification result is between users; identification of potentially malicious classifications, etc). Similar tools will be employed for validating the Moon Zoo user databases and a range of data reduction techniques will be employed to turn raw data collected by the website into science-ready outputs.

"Users flag unusual features in the Forum, so discoveries can be discussed"

Moon Zoo project status

As of October 2010, since its launch the Moon Zoo website has had 234 230 visits by 168 830 people, of whom 20 872 have undertaken scientific tasks. People have visited from all over the planet, from more than 100 countries, while 1 208 759 images have been examined and 4 309 730 craters or other features of interest have been identified. We are collecting more and more data by the minute and Moon Zoo is now poised to deliver high-quality data to address key questions in lunar science. At the same time, Moon Zoo is an excellent education tool to help promote lunar science and exploration and engage the public in learning about the process of scientific discovery. We hope that you enjoy it. Please go to our website http://moon.zooniverse.org for further information. ●

Moon Zoo team members: Irene Antonenko (Univ. Toronto), Ryan Balfanz (SIUE), Matt Balme (Open University), Steven Bamford (Nottingham), Barach Blumberg (NASA AMES), Neil Bowles (Univ. Oxford), Roberto Bugiolacchi (Max Planck Institute, Germany), Jimmy Carter (Univ. Aberystwyth), Clark Chapman (Southwestern Research Institute), Anthony Cook (Univ. Aberystwyth), Cari Corrigan (Smithsonian Institution), Ian Crawford (UCL/Birkbeck), Doris Daou (NLSI), Lucy Fortson (Univ. New Mexico), Pamela Gay (SIUE), Peter Grindrod (UCL/Birkbeck), Mark Hammergren (Adler), Katherine Joy (LPI), Michelle Kirchoff (SwRI), Chris Lintott (Univ. Oxford), Noah Petro (NASA), Stuart Robbins (Univ. Colorado), Doug Roberts (Adler Planetarium), Mark Sands (SIUE), Delia Santiago (NASA Lunar Science Institute), Kevin Schawinski (Yale University), Arfon Smith (Oxford), Mark Subbarao (Adler Planetarium), John Wallin (George Mason University), Shoshana Weider (Carnegie).

Acknowledgments. Thank you to all Moon Zoo classifiers for their invaluable contributions to the project. We also give special thanks to Julia Wilkinson and her team of moderators, Thomas Jennings and Geoff Roynon, for all their help and efforts in maintaining the Moon Zoo Forum. The Leverhulme Trust provided financial support to develop Moon Zoo software and manpower. NASA Roses Grant NNX09AD34G provided education support. The RAS kindly provided financial support to help KJ to attend Moon Zoo related meetings.

Further information

Citizen Science Alliance http://citizensciencealliance.org
Galaxy Zoo http://galaxyzoo.org
Moon Zoo http://moon.zooniverse.org
Moon Zoo blog http://blogs.zooniverse.org/moonzoo
Moon Zoo Forum http://forum.moonzoo.org
Zooniverse http://zooniverse.org

References

Antonenko I *et al.* 1995 *Earth, Moon and Planets* **69** 141–172.
Bandfield J L *et al.* 2010 in *Lunar and Planetary Science XLI* Abstr. no. 2012.
Bart G D 2007 *Icarus* **187** 417–421.
Campbell B A and Hawke B R 2005 *J. Geophys. Res.* **110** E09002 doi:10.1029/2005JE002425.
Chin G G *et al.* 2007 *Space Science Revs* **129** 391–419.
Gault D E and Wedekind J A 1978 *9th Lunar and Planetary Science Conference* 3843–3875.
Ghent R R *et al.* 2005 *J. Geophys. Res.* **110** E02005 doi:10.1029/2004JE002366.
Ghent R R *et al.* 2010 in *Lunar and Planetary Science XLI* Abstr. 1889.
Hartmann W K 1977 *Icarus* **31** 260–276.
Hawke B R *et al.* 1985 *Earth, Moon, and Planets* **32** 257–273.
Hawke B R *et al.* 2005 *J. Geophys. Res.* **110** E06004 doi:10.1029/2004JE002383.
Ivanov B A *et al.* 2000 in *Collisional Processes in the Solar System* eds H Rickman and M Marov (ASSL, Kluwer Academic) 357.
Lintott C J 2008 *MNRAS* **389** 1179–1189.
Moore H J *et al.* 1980 *Moon and Planets* **23** 231–252.
Neukum G *et al.* 2001 *Space Science Revs* **96** 55–86.
NRC (National Research Council) 2007 *Report on the Scientific Context for the Exploration of the Moon.*
Oberbeck V R 2008 Comment on: Constraints on the depth and variability of the lunar regolith, by B B Wilcox, M S Robinson, P C Thomas, B R Hawke *Meteoritics & Planetary Science* **43**(4) 815–817.
Quaide W L and V R Oberbeck 1968 *J. Geophys. Res.* **73** 5247–5270.
Robinson M S *et al.* 2010 in *Lunar and Planetary Science XLI* Abstr. no. 1874.
Stöffler D *et al.* 2006 in *New Views of the Moon* eds B L Jolliff, M A Wieczorek, K Shearer, C R Neal *Rev. Mineral. Geochem.* **60** 519–596.
Urbach E R and T F Stepinski 2006 *Planetary and Space Science* **57** 880–887.
Warren P H 1994 *Icarus* **111** 338–363.
Wilcox B B *et al.* 2005 *Meteoritics & Planetary Science* **40** 695–710.
Wilhelms D E *et al.* 1978 in *Lunar and Planetary Science XIX* 3735–3762.