AN X-RAY ULTRAMICROSCOPY STUDY OF APOLLO 11 LUNAR REGOLITH C. Kiely and C.J. Kiely, Department of Materials Science and Engineering, Lehigh University, Bethlehem, PA 18015, USA. cak4@lehigh.edu and chk5@lehigh.edu

Introduction: Forty years of research has provided a lot of information about the chemical and physical properties of lunar regolith.[*e.g* .1]. To date, however, the only way to examine the internal structure of these tiny particles has been to find a particle that has been fractured or to deliberately slice and mechanically polish a collection of particles embedded in a resin. Now there is a new technique called X-ray ultramicroscopy (XuM) that enables the internal structure of a whole particle to be imaged in a non-destructive manner. Pioneered at the CSIRO, Australia [2], XuM utilizes the small spot source of X-rays generated in a scanning electron microscope when the incident electron beam is focused onto a platinum target. The divergent X-ray beam produced then passes through the sample and a projection image is collected by an X-ray sensitive CCD camera (see Fig.1). X-ray imaging of lunar regolith has been carried out once before using the beamline 13M (GSECARS) of the DOE Advanced Photon Source [3] but X-ray ultramicroscopy offers more convenience and a much improved image resolution. An excellent overview of the XuM technique has been given by Brownlow *et al*.[4].

Unlike many other microscopy techniques, this type of imaging does not require any focusing optics - the entire XuM image is always in focus. The resolution is highly dependent on the source spot size and the magnification can be altered by simply moving the sample closer to or away from the target. There are two mechanisms that give rise to the contrast in the XuM images: absorption and phase contrast. The latter highlights cracks and pores contained within the sample that are often difficult to see with conventional X-ray imaging techniques.

One particularly nice feature of this technique is the ability to rotate the sample through 360º taking sequential images every few degrees. This yields a more global view of the internal structure of a particle and can help prevent erroneous conclusions being drawn from a single 2-D image. For example, a plate-like inclusion could be mistakenly be identified as a needle-like feature when viewed 'edge-on' in a single 2D projection image. Collecting a systematic series of images also enables rotational movies to be made giving a fascinating 3-D view of a particle's internal structure.

Results and Discussion: A useful way to highlight the power of this new technique is to compare the corresponding secondary electron and XuM images of the same particle. This allows both the surface morphology and internal structure to be viewed side-by-side as shown in Figure 2. The roughened area on top of the opaque glassy spheroid, (Fig. 2(a)), suggests that this particle, formed by splashing of molten regolith during a micro-meteoroid impact, may not have completely solidified before landing back on the lunar surface. The SEM image also shows several tiny holes indicative of internal bubbles, formed by the evolution of trapped gases in the melt, just breaking through the surface. The X-ray image (Fig 2(b)) reveals that the particle actually contains a myriad of internal pores, the largest of which has a diameter of 63µm. Rotation of the sample by 90^{o} (Fig 2(c)) reveals that this pore has not penetrated the surface. Also visible in Figs 2(b) and (c)) is a more dense inclusion (almost certainly containing iron) which is probably a very thin plate of ilmenite. McKay *et al.*, [5] have previously reported the existence of an ilmenite

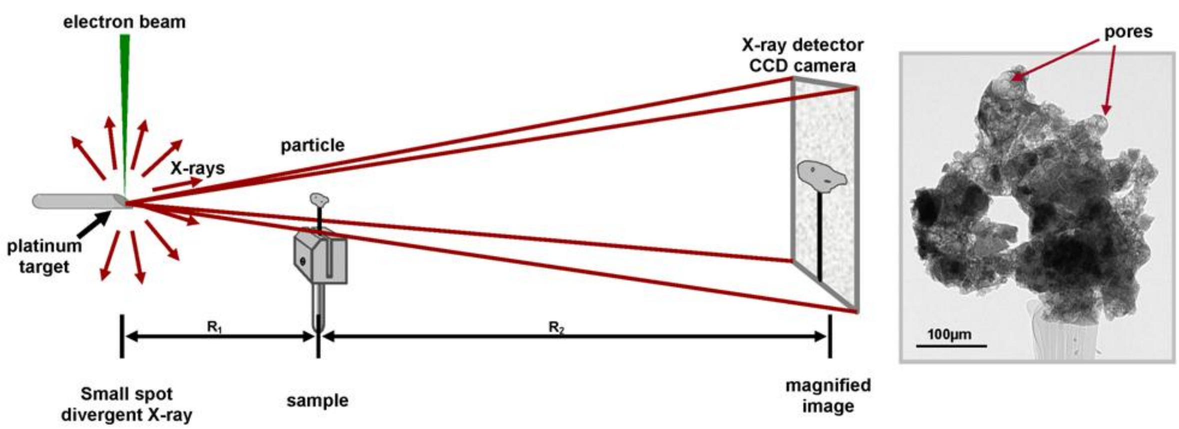

Fig.1 Schematic diagram of an X-ray ultramicroscope showing a 2-D projection image of an agglutinate particle.

crystal partially embedded in a similar glassy sphere

Internal pores are also found in other glassy particles as shown in Fig.3. These ellipsoid, teardrop and dumb-bell shape particles all contain pores which on closer examination are often not quite spherical. There has clearly been some movement in the viscous melt after the bubbles have formed. One of the contentious debates in the 1970s was whether the dumb-bell morphologies were formed as a result of (i) the translational break-up of a molten regolith spray or (ii) from droplets which having gained rotational momentum undergo centrifugation causing the break-up [*e.g.* 6,7]. There is experimental evidence in the literature to support both mechanisms. In the XuM micrograph of the dumb-bell shown in Fig. 3, both the pores and the inclusions are clearly visible. The pores do appear to have migrated towards the center of the dumb-bell whereas the darker inclusions are located at its extremities. While this XuM image seems to support the centrifugation mechanism , many more particles of this type would need to be examined before a definite conclusion can be drawn.

Summary: X-ray ultramicroscopy has been shown to be a powerful tool for non-destructively examining the internal structure of lunar regolith particles. The fact that the entire 2-D projection image is in focus and the ability to collect a rotational series of images means that a much more realistic three-dimensional view of the internal structure of a particle can be obtained. The glassy component in many agglutinates and spheroids examined in this study was much more vesicular than expected. While XuM does not negate the need to carry out petrographic analysis, it may prove to be an invaluable pre-screening tool to pinpoint a particular feature of interest in a particle. Being able to collect scanning electron and X-ray micrographs from the same particle may also provide useful evidence to discern between competing models on the evolution of lunar regolith structures.

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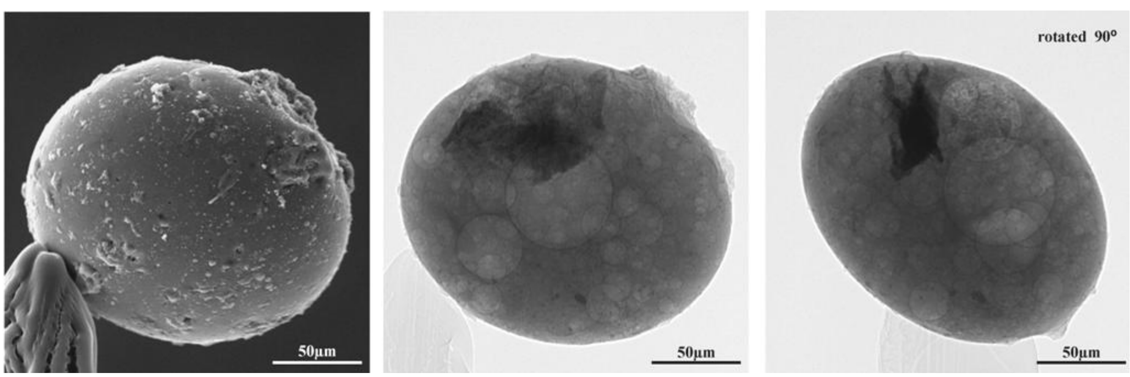

Fig.2 Scanning electron and X-ray ultramicrographs of an opaque glassy sphere.

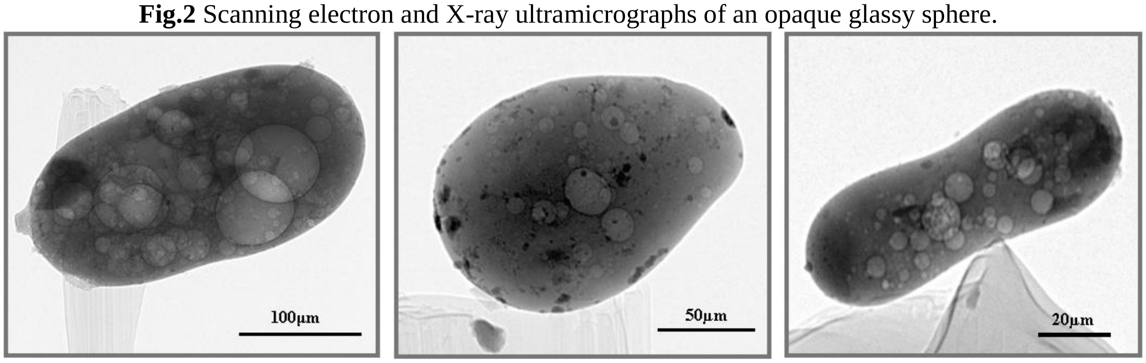

Fig.3 X-ray ultramicrographs of opaque glassy particles with ellipsoid, teardrop and dumb-bell morphologies.