CHEMIN AS A TOOL FOR LUNAR EXPLORATION: PRELIMINARY MEASUREMENTS OF LUNAR SAMPLES.

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Introduction: The CheMin X-Ray Diffraction/X-Ray Fluorescence (XRD/XRF) instrument has been chosen to fly on the 2009 MSL mission to Mars (1). A similar instrument would add significant capability to lunar surface measurements on robotic missions and at a lunar outpost. We have measured the mineralogy of lunar soil samples a using newly developed field-portable version of the flight instrument, called miniCheMin (sold commercially by inXitu as *Terra*). The preliminary results indicate that miniCheMin can determine the abundances of minerals and glass in a range of lunar soil samples.

The miniCheMin Instrument: CheMin (short for *Chemistry* and *Mineralogy*) is a field portable, miniaturized XRD/XRF instrument. The miniCheMin instrument consists of a power supply, CoKα X-ray tube, sample holder, CCD detector, control electronics, computer and battery/power system. The transmission sample holder consists of a 5 mm diameter wafer-shaped cell, bounded by 7 µm mylar or Kapton windows held apart by a 175µm spacer. Powdered sample is flowed into the cell through an opening at the top. The sample holder employs a sonic frequency piezoelectric shaker system, which causes the powdered sample material to flow with a convection pattern similar to a liquid, exposing all grains to the beam in random orientation. This allows CheMin to use coarsely ground powder not suitable for standard XRD systems.

The miniCheMin detector consists of a thermoelectrically cooled 1024X256 deep-depleted CCD housed in a back-filled dry nitrogen chamber fitted with a thin Be window. X-rays from the sample pass through the window and are directly detected by the CCD.

Lunar Scientific Targets: CheMin will be valuable for characterizing a variety of lunar geological targets, as well as for analyzing resource potential and the products of resource extraction experiments. Three (of many) examples are discussed briefly below.

Lunar pyroclastic deposits. Lunar dark-mantle deposits are attractive targets for exploration and resource extraction. Interest in these deposits for lunar science stems from their primitive igneous compositions, providing valuable clues to mantle composition and processes. The deposits are also useful for understanding pyroclastic eruptions on airless bodies. For this purpose it is useful to be able to quantify the relative abundances of glass and crystalline materials.

Evolved lunar lithologies. The lunar magma ocean and subsequent magmatic processes led to a variety of magmas enriched in incompatible trace elements. Such evolved rocks are important both for understanding the formation of the lunar crust and as potential resources. These rocks have experienced extreme igneous differentiation through extensive fractional crystallization, sometimes involving silicate liquid immiscibility, possibly on a large scale.

Permanently-shadowed polar regions. The Moon has an extremely small tilt of its rotation axis relative to the ecliptic. Near the poles, impact craters and other topographic lows are permanently shaded from the Sun, raising the possibility that volatiles could be trapped in the shadows (2). Although lunar polar temperatures have not yet been directly measured, thermal models suggest that maximum surface temperatures of less than 60 K are likely common, and 25 K is possible. There are many potential sources, emplacement mechanisms, and loss mechanisms for lunar polar volatiles. Moreover, many interesting chemical processes might have operated, producing products ranging from clathrates to hydrated minerals.

Testing CheMin Capabilities with Lunar Samples: These three types of targets differ greatly in their mineralogy. As a first step in testing the efficacy of CheMin for understanding the genesis of lunar materials, we tested a variety of samples.

High-Ti mare regolith fines. 10084,78
Low-Ti mare regolith fines. 12001,893
Fra Mauro regolith fines 14163,882
Highlands regolith fines. 61501,25
Orange glass (pyroclastic). 74220,66
Green glass (pyroclastic). 15427,63

Artificial red glass. High-TiO_2 (18 wt%) glass produced under lunar oxidation conditions with a composition similar to the highest Ti lunar pyroclastic glass.

Artificial green glass. Low-TiO_2 (1 wt%) glass with a composition similar to Apollo 15 green glass.

Procedures. Samples with grain sizes of < 150 µm and weighing ~50 mg were placed inside the mini-

CheMin sample holder and exposed for about 4 hours each. The resulting diffraction patterns were quantified using Rietveld refinement, a structurally based full-pattern fitting technique. This allowed us to determine the abundances of minerals present at levels greater than about 1 wt% and the abundance of silicate glass.

Results: XRD patterns are shown in Figs. 1 and 2. Soil patterns clearly show the presence of variable amounts of the major minerals plagioclase, augite, and ilmenite. Plagioclase, for example, is highest in the Apollo 16 sample from the lunar highlands, whereas the ilmenite peak is strongest in the Apollo 11 sample from a high-Ti maria. In addition, the broadly elevated background indicates the presence of amorphous material, in this case silicate glass. This is shown prominently by the patterns for the two artificial glasses (Fig. 2). This diffuse amorphous scattering and its position are a measure of the bond distances in the glass, which are a function of composition. Calibrating this is an area of future research.

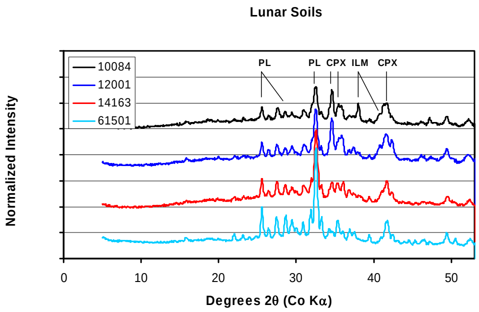

Fig. 1 XRD patterns for lunar soils. Locations of prominent peaks for major minerals are indicated. Note broad amorphous scattering, which indicates the presence of glass (cf Fig. 2). PL=plagioclase, CPX=clinopyroxene (augite), and ILM=ilmenite.

The lunar pyroclastic glass samples have characteristic broad amorphous scattering features and also contain prominent peaks for plagioclase (especially in the Apollo 15 green glass), ilmenite and augite. This shows that CheMin is capable of quantifying the abundances of glass and crystalline materials on a mission to a pyroclastic deposit. The abundances of glass and crystals are pertinent to understanding the eruption mechanisms of such deposits.

We compare our results with those obtained by point-counting (3,4) using scanning electron microscopy in Fig. 3. Although the agreement is not perfect at this stage of our research, the results are promising. We generally overestimate the glass abundance, probably due to a restricted database of glass compositions in our fitting program. We also underestimate ilmenite, perhaps due to the presence of armalcolite, but in general our results are within 10% of those obtained by the elaborate and time-consuming point-counting procedure used by L. A. Taylor and his colleagues (3,4). A more extensive dataset for lunar mineral and glass separates will greatly improve the results.

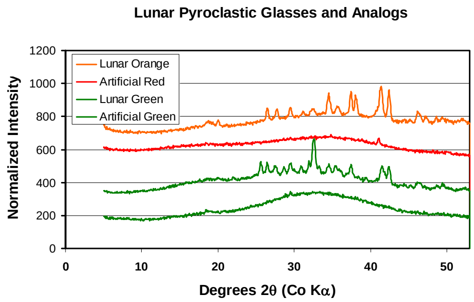

Fig. 2. XRD patterns for lunar pyroclastic glasses and artificial analogs. Note broad amorphous scattering feature, especially evident in crystal-free artificial glasses. Lunar glass samples contain substantial amounts of crystalline materials.

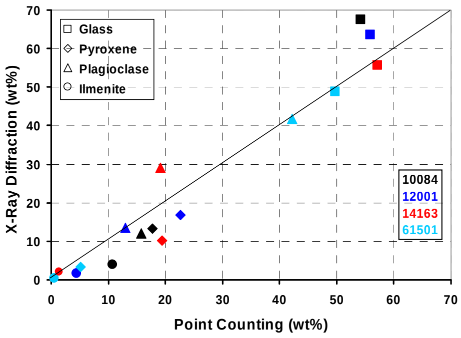

Fig. 3. Comparison of pointing counting using SEM (1,2) with our results using CheMin. (For the Apollo 16 comparison we used point counting data for 61141 because [4] does not report data for 61501.)

Conclusions: Our data show that CheMin can determine the mineralogy, including the total glass content, of lunar regolith and pyroclastic samples. It will be a useful exploration tool on lunar robotic missions and could be invaluable in analyzing samples at a lunar base to plan field work and screen samples before delivery to Earth. Such lunar base analytical work would have little impact on astronaut time. The instrument can also be used to analyze a large number of Apollo regolith samples to determine the abundances of minerals and glass for other studies, such as calibrating visible-near infrared spectroscopy.

References: [1] P. Sarrazin et al., (2005). *Powder Diffraction* **20**(2), 128-133. [2] Watson, K. et al. (1961) *J. Geophys. Res.* **66**, 1598-1600. [3]Taylor, L.A. et al. (2001) *J. Geophys. Res.***106**,27985-27999. [4] http://web.utk.edu/%7Epgi/data.html).