CALCULATIONS OF THE FLUXES OF 10-250 keV LUNAR LEAKAGE GAMMA RAYS. K. J. Kim[1], R. C. Reedy[1], and O. Gasnault[2], [1]Institute of Meteoritics, MSC3-2050, 1 University of New Mexico, Albuquerque, NM 87131-1126 USA (kkim@unm.edu; rreedy@unm.edu), [2]Centre d'Etude Spatiale des Rayonnements, 9 avenue Roche, 31028 Toulouse, France (Olivier.Gasnault@cesr.fr)

Introduction: The gamma rays measured above the surface of planetary objects can be used to study that surface's composition [e.g., 1]. Previous and current measurements have mainly used gamma rays with energies >500 keV, although most missions measured down to ~100 keV. Gamma rays above ~100 keV are very penetrating and thus hard to collimate, so previous missions to the Moon and Mars have measured gamma rays arriving from the entire visible surface. The spatial resolution was not better than about the distance above the planet's surface.

The continua observed on previous missions down to ~100 keV increases significantly with decreasing energy [2]. These continua make it hard to measure the fluxes of gamma-ray lines with energies below ~500 keV, and all elemental analyses have used higher-energy gamma rays, usually using only lines.

The continuum can be used to study components of the lunar composition. The lunar continuum is a good measure of the abundance of the natural radioactive elements K, U, and Th, using the continuum between 0.55 and 2.75 MeV [3] and between 450 and 480 keV [4]. Fourier transforms of continua have been proposed to determine composition [5].

Gamma rays below ~200 keV can be collimated, so could possibly be used to improve the spatial resolution on the planet's surface. Also, such gamma rays can be measured with high efficiency. It has been proposed to use gamma rays between 20 and 250 keV to study uranium and thorium in the Moon on the planned Indian lunar orbiter Chandrayaan-1 [6].

The planetary continua below ~100 keV have not been measured, so we calculated the continua of 10-250 keV gamma rays for a range of lunar compositions. We explored what information can be determined from these gamma-ray continua.

Calculations: The numerical simulations were done using the MCNPX (Monte Carlo N-Particle eXtended) code at UNM and the GEANT 3 code at CESR. At UNM, version 2.5.d of the MCNPX code and the CEM (Cascade-Exciton-Model) option were used with several libraries for nuclear interactions and gamma-ray production. This code has been well tested using cosmogenic nuclides [e.g., 7] and reproduces the basic shape of the measurements by the gamma-ray spectrometer on Mars Odyssey. The calculations of the GEANT 3 code at CESR agree well with the measurements at Mars [8]. The results calculated here with with GEANT 3 included the GCALOR and GLECS packages for low energies. The calculations were not normalized to an incident GCR flux and thus are only relative among each codes' compositions.

A range of lunar compositions was used. These compositions have been used previous to scope lunar measurements [e.g., 9]. They range from ferroan anorthosite (FAN) and highland compositions sampled by lunar meteorites with low abundances of Ti and Fe to rare-earth-rich KREEP and to a mare composition with high Fe and Ti (Apollo 17). We also included the lunar-meteorite composition with the H in 2% water to study polar H enrichments.

Results: The calculated relative gamma rays fluxes from MCNPX, which includes the continuum and any gamma-ray lines produced using the adopted libraries, and GEANT, which only calculated the continuum, are shown in Figs. 1a and 1b, respectively.

The results are in general agreement, but differences can be seen, especially the relative intensities. We will work on understanding these differences. Both codes give maxima near ~100 keV and very sharp decreases at lower energies that vary systematically with composition for both sets.

Discussion: The shapes of the gamma-ray continua at lower-energies are sensitive to the composition. Below ~100 keV, the continua decrease significantly, due to the much higher attenuation of photons at such energies. Above ~200 keV, the attenuation of photons is almost independent of lunar composition (e.g., as calculated the XCOM web-calculator at NIST). However, below ~100 keV, attenuation of photons is very sensitive to composition. The photon attenuation coefficients (in cm^2/g) at 100, 50, and 20 keV for Apollo 17 relative to FAN are 16, 57, and 83% higher, respectively. This variation in attenuation explains the shape of the continua below ~100 keV.

Above ~150 keV, the level of the continua, especially as calculated by MCNPX (Fig. 1a), also varies with composition. The change in the continua in these calculations is mainly caused by the higher production of secondary neutrons by higher mass elements (mainly Ti and Fe), as observed by Lunar Prospector [10] and as calculated for the Moon [10,11]. There are ~30% more neutrons made by the Apollo 17 composition than by the highland compositions. The continuum calculated with MCNPX for the 2% water case is slightly higher than the dry lunar meteorite case, but the enhancement is probably too small to study lunar H contents. For the Moon, the continua above ~100 keV will be affected by decay of K, U, and Th, so corrections for these naturally radioactive elements needed to be made in studies using the magnitude of the continua >100 keV.

In Fig. 1a, there are only a few weak gamma-ray lines. There is a fairly strong peak at 30 keV, probably due to a thermal-neutron-capture gamma ray with ^{27}Al at 30.6. Other peaks are very weak and would be hard to measure. The identified peaks in the MCNPX-calculated spectra (and their probable sources) are at 122 keV (excited ^{57}Fe made by both capture and scattering reactions), 126 keV (excited ^{55}Mn), 159 keV (excited ^{47}Ti), 171 keV (excited ^{27}Al), 84 and 212 (capture reactions with ^{55}Mn), 228 keV (excited ^{46}Sc made from Ti), and 89 and 182 keV (capture reactions with Gd). The 159 and 228 keV gamma rays have been observed from the Ti can of the Mars Odyssey GRS but, like the gamma rays in our calculations, are hard to see above the high continuum [2]. The peaks calculated in Fig. 1a depend on the specific library used with MCNPX. However, the above gamma rays are the most of main lines expected from major and minor elements in our lunar compositions.

We did not calculate fluxes of gamma rays from the decay chains for Th and U, but there are several below 250 keV [cf., 12], such as 63.29, 92.38, and 92.80 keV from the U daughter ^{234}Th and several near 186 keV from U decay. If radon diffusion is important, the U daughter ^{210}Pb and its gamma ray at 46.54 keV could be enhanced at the surface.

Conclusions: Our calculations show that measurements of ~10-250 keV gamma rays could be used to study planetary composition. Most x rays from the Moon are below 10 keV, but some x rays from trace elements will be present in lunar spectra up to ~115 keV from U, although emission probabilities of x rays from U are less than its stronger gamma rays [13]. These gamma rays could be readily measured using large area detectors of Ge or CdZnTe and also could be collimated to improve spatial resolution. Changes in the measured continua indicate the relative amounts of heavier (Ti, Fe) elements, which can delineate major lunar geological units. The measurements are sensitive to radioactive elements, allowing the mapping of KREEP. A few low-energy gamma-ray lines might also be observable.

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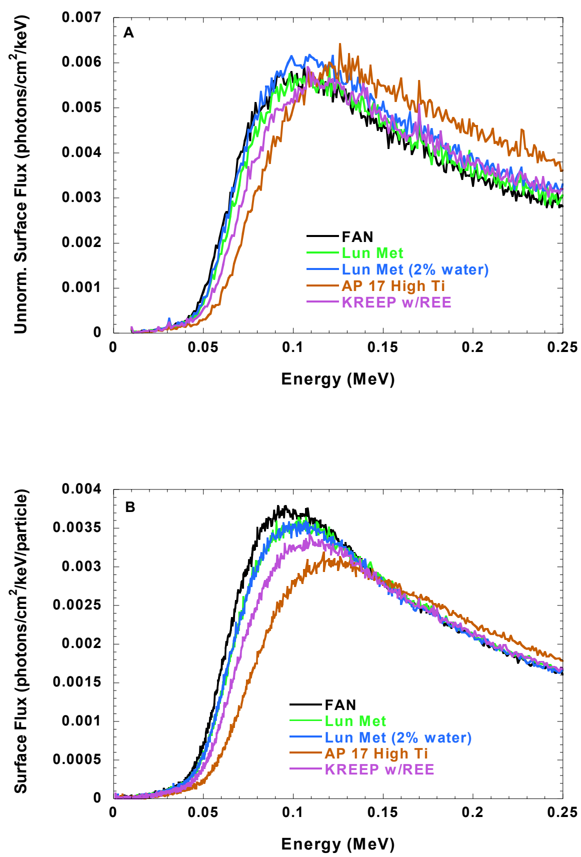

Figs. 1a and 1b. Calculated relative fluxes of gamma rays escaping the Moon for 5 lunar compositions using the MCNPX (1a) and GEANT 3 (1b) codes.