REEEVALUATING ELEMENTAL ABUNDANCE ON THE MOON

Kenneth E. Dobbs
Department of Political Science
University of Hawai‘i at Mānoa
Honolulu, HI 96822

ABSTRACT

Gamma ray spectrometry is important for chemical analysis of elements in surfaces of planetary bodies. The Lunar Prospector mission used a Bismuth Germanate (BGO) scintillation detector to the moon to measure Gamma rays, as is the current Dawn mission to Vesta and Ceres [1,2]. The low resolution of BGO detectors can make analysis of Gamma ray spectra very difficult, with peak area contributions not directly caused by the element identified by that peak [3]. For the current Iron, Magnesium, and Titanium abundances of the moon, the Lunar Prospector’s Gamma ray spectra were used with an “unmixing algorithm” with the Monte Carlo N-Particle eXtended (MCNPX) program. The goal of this project was to analyze the results of this method, compare it with a method used in a previous study, and evaluate the iron abundance on two locations on the moon. After analysis on the Imbrium and Tranquillitatis Mare using both methods, the Iron abundance has been found to be in conflict with current listed abundances, and suggests that current methods may need careful review.

INTRODUCTION

The Lunar Prospector was launched on January 7, 1998, and was designed “for a low polar orbit investigation of the moon, including mapping of surface composition and possible polar ice deposits” [4]. Mapping of surface composition was determined using gamma ray and neutron spectroscopy using detectors located on booms extended away from the craft’s main body [2]. The polar orbit operated at three altitudes over the course of the mission, beginning at 100km, to 40 km, down to 30km [4]. It is from this lowest orbit from December 19, 1998 until the mission’s end on July 31, 1999 that we have taken the Level One spectra from the gamma ray spectrometer. The level one data has taken five degree by five degree areas of the moon, called pixels, and created integrated spectra for these regions over a given unit of time, thirty-two seconds [5]. This time was chosen because it is time required by the detector to take a spectrum. Each spectrum has 512 channels ending at 9.1MeV, in 1790 total pixels for the moon, for this binning method [6]. Some of these spectra had to be removed because of interference experienced by solar events, which resulted in unusual spectra features. Still other spectra had to be removed due to electronic error, where the data sent from the Lunar Prospector lacked key coding which resulted in unidentifiable, and unusable spectra.

Understanding of background is incredibly important to planetary gamma ray spectrometry. Interference from the detector itself, from the spacecraft, and from cosmic radiation all influences the spectra and analysis of the spectra. The background radiation, as well as the contribution of other elements to the peak area must be taken into account during analysis, as well as when evaluating the results [3].
The method currently established by T.H. Prettyman et al in 2006 is compared with the peak area analysis of High Purity Germanium (HPGe) and BGO detectors in 2012. Dr. Prettyman’s methods consisted of a complex system of simulations checked against “ground truth,” regolith, meteorite and drill samples, taking into account multiple geometric points of consideration [6]. Prettyman’s work focused on the “High1” altitude spectra “which had the longest integration time” [6]. The simplest explanation for the method can be described as; 

\[ C = RG(\lambda, E) \] or (C) counts are equal to the (R) total Gamma rays produced at surface area per unit time, by the (G) effective cross-section of the detector, by the (\lambda) latitude of the craft by the (E) energy of the Gamma ray. R was calculated using the MCNPX program using the abundance of an element, the number of gamma rays created per reaction, the number of reactions per neutron, and the production rate of neutrons by cosmic rays. These calculations were compared with regolith samples from the Apollo and Luna missions, and were used under the assumption of a homogenous surface composition [6]. This assumption was based on repeated bombardment over time [6]. The results of this work have created several abundance maps for Iron, Iron Oxide, Titanium, Potassium, Uranium, and epithermal and thermal neutrons. The Iron abundances have been logged according to latitude and longitude by pixel, and give the Iron abundance in weight percent [7].

The methods used in this project consisted of understanding the algorithms and methods used in previous studies specifically that of Dr. Prettyman et al, understanding elemental gamma ray line strengths, identification and analysis of specific regions on the moon, and analysis of the results of the comparison. Analysis on the spectra was completed in IGOR using the Multi-peak fit 2 subroutine. Graphing of spectra, comparison, and logging of data was completed with Excel.

**METHODS**

The beginning of the project consisted of careful reading and review of the methods of analysis that created the current Lunar Prospector based Iron and Titanium maps. It was not immediately apparent the role that MCNPX played in the analysis of the spectra, and was believed to have been used to analyze the spectra themselves. However, this careful review showed that the program was used for many purposes, but direct analysis was not one of them. Instead, MCNPX was used to calculate the number of gamma rays produced within the lunar surface that would reach the Lunar Prospector and then interact with the detector. This calculation was then set against regolith samples from the Apollo and Luna missions and lunar meteorites. However, these were used as points of reference, and not necessarily as points of calibration for the system. Additionally, the presence of neutron absorbing, but low abundance elements in the highland regions immediately surrounding the mare, were taken into account and theorized to complicate the identification of Iron in the mare, resulting in previously low Iron abundances [6]. MCNPX was not available during this project, and as such, the results of the simulations could not be duplicated. The results came to the forefront of analysis, although the methods used to create these results were carefully analyzed and considered throughout the process. By understanding the methods used and the reasons behind these decisions gives greater insight into the results, and understanding why there may have been discrepancies between the Prettyman results, and our own. Our method was compared with the peak area analysis, which compared the total peak area derived from the corresponding element between
HPGe and BGO detectors [8]. The Lunar Prospector ran a BGO type detector, and so this relationship between peak areas as a percent of total was used in this analysis.

After this review, it was necessary to identify what gamma ray lines to focus on in analysis, and what lines may cause interference in the peak area analysis. Iron and Titanium abundances were of immediate interest, and consequently focus was oriented on gamma ray lines produced by interactions with those elements. Additionally, this was focused further to isotopes considered to be common, as well as those isotopes that would be naturally created by various interactions. Initially this consisted of full spectrum consideration for both elements. However, peak area analysis requires an identifiable peak within the spectrum, and Titanium does not have its own identifiable peak in the lunar spectra. Without the ability to directly analyze a Titanium peak, the project had to move forward focusing on Iron peaks instead. There are two primary Iron peaks in the spectra, correlating with the 846KeV and 7645KeV gamma ray lines. Previous peak area analysis showed that the 846KeV peak experienced contributions from sixteen other gamma ray lines in a basalt target. This resulted in less than forty percent of the BGO peak area derived from the identified gamma ray line [8]. However, the 7645KeV peak area only experienced contributions from two other weak gamma ray lines, resulting in eighty-six percent of total peak area derived from the Iron gamma ray line [8]. The lack of interference is likely due to the high energy gamma rays produced by neutron capture, where the lower energy gamma rays are mostly produced by neutron scattering. The high peak area percent in the BGO spectrum means that analysis of that peak more accurately reflects an analysis of that gamma ray and that element.

In addition to focusing on a specific region of the spectra, it was prudent to focus on a specific region on the moon, and compare it to another region to verify the methods used. Two mare on the moon were chosen to have relatively higher and lower iron abundances. There are many regolith samples from the mare, allowing for multiple points for comparison. The Imbirum and Tranquillitatis Mare were chosen for these purposes. Although there were several other locations considered, such as the Oceanus Procellarum, the defined edges of the mare against the highlands allowed for a focused analysis on basalt type material. The mare had to be defined according to longitude and latitude, and the pixels were then mapped onto these locations. Iron maps were then created using current iron percentages, but set to a new scale that was created to allow for changes in the hundredth percent to be reflected visually.

The spectra found for these two mare were then fully analyzed in IGOR, and the results of the 7645KeV logged focusing on the background. Slight differences in counts caused the backgrounds to fluctuate a great deal in the program. As a result, an optimal method of analysis was created to manual shift the background, and channel extremes to provide a proper fit. The program GANY was also used, but required an additional manipulation of the data. GANY was not able to use counts with a decimal, as was the case in the integrated Lunar Prospector Level One dataset. The counts had to be multiplied by 1000 in order for GANY to be able to read and analyze the spectra. As such, this changed the spectra from the number of counts per thirty-two seconds, to thirty-two thousand seconds. Because a concern over the number of variables created was a focal point for the review of previous analysis methods, GANY was unfortunately ruled out. It is important to note, however, that the spectra analysis on these spectra resulted in an excellent background fit for each spectra with very little adjustments necessary. Had the spectra been total counts instead of integrated spectra, GANY may have been the preferable
method for analysis. That being said, IGOR provided excellent results in peak area analysis once the program was better understood.

Figure 1: High energy region in IGOR, pixel 1260 of the Imbrium Mare

Peak areas of the spectra were then plotted according to the area by the current iron abundance. Both Imbrium and Tranquillitatis were graphed separately and then together in order to compare. It was assumed that the peak area and abundance should fall along a general trend, as the peak is directly related to the number of gamma rays measured by the detector. Since the number of gamma rays produced is linked to the abundance of the element, the peak area should increase proportionally to the abundance increase. Once this general trend line was established, the peak areas were multiplied by the slope of the line to create an “ideal” abundance to peak area. This was to compare the results of the previous iron analysis, and to create a new Iron abundance based on Peak area analysis.

Figure 2: Peak Area comparison to Iron abundance, where Circles are Tranquillitatis spectra, Diamonds are Imbrium spectra, and Triangles are calculated abundances using the general trend line
RESULTS

Analysis of the spectra and of their peak areas showed a disconnect between the calculated and given Iron abundances. The peak areas used to create the calculated abundances were also multiplied by the percent of peak area from total for the 7645KeV Iron line. This, along with the slope of the calculated trend-line, still did not match with the given Iron abundances. The Apollo missions had been used as a reference point in the MCNPX simulations, and so these Iron abundance results were graphed together with the current Iron abundances, and found to have little to no relation. However, there was a very strong correlation between the calculated and the Apollo abundances. This was determined by utilizing three Apollo mission landing sites that existed within spectra that were analyzed by this project, and then compared with the calculated, and the current Iron abundances using the same peak area for all three. The resulting graph showed this correlation between the calculated and the Apollo Iron abundances.

![Figure 3: Peak area comparison. Diamonds are Apollo samples, Squares are calculated, Circles are current abundances](image)

The calculated abundances were then used to create new Iron abundance maps for the two mare. The difference in Iron percent varied from a five percent difference to a 0.2 percent difference. Typically, the calculated abundances were lower than the current abundances with very few exceptions. The data was reviewed several times to ensure that the method was sound. A direct comparison with regolith samples at three locations also confirms this method of analysis.

Titanium did not produce an identifiable peak in the spectra, and so was not able to be analyzed by this method. However, the Kaguya spectra could be used to help identify Titanium abundance, as the higher resolution of HPGe detectors would make analysis of those peaks possible. BGO detectors poor resolution also makes identification of abundances for elements without a strong peak not possible for peak area analysis methods. A comparison between Lunar
Prospector spectra and Kaguya spectra would be helpful to identify these elements without a major BGO peak.

The simulation methods that had been used to create the current Iron abundances were not able to be duplicated, as the MCNPX program was not available. Additionally, the extremely complex methods derived by that team would require a great deal more than the time that was available for this project. A future comparison would look at these methods, duplicate them, and then compare these duplicated results with the original, and then with the peak area analysis. A major issue with the previous method, aside from its complexity, is the number of variables dependent upon simulation. An interesting review would be to take the results of the BGO from the Lunar Prospector, compare it to the Kaguya mission, which had a smaller footprint, and then directly compare these with regolith samples. The peak area method should also be compared directly to more points of data than what was available at the time, specifically the results of the Sodium Iodide (NaI) detector of the Apollo mission.

**CONCLUSION**

Review of the MCNPX method and comparison with the peak area analysis has shown that the previous method may have overestimated Iron abundance in the Lunar Mare by a variable amount upwards of five percent. Although the previous methods took into account several important factors regarding amount of gamma rays measured versus number likely produced using sophisticated programs, the end results are not in concert with any other previously established method, including the peak area analysis. When such a complex method is used, with multiple points dependent upon the simulation of other points, too many uncontrolled variables become present. It is also suggested that the influence of Gd and Sm were overemphasized, and that the low abundance would not cause as great a reduction in neutron absorption in the mare. The 846KeV line of Iron, although heavily surrounded by many other peaks, was also analyzed and compared in the peak area analysis. After a reduction by the peak area from total for that region, there was still a two to seven percent difference in the current Iron abundance versus the peak area method. There is a similar difference between the current abundances, versus the Apollo, Clementine, and Kaguya percentages, albeit all three use different detector types. It would be prudent to compare the peak area method with multiple data points in each of these missions as well. Further analysis on lunar spectra should continue to take into account several important variables used in the current analysis methods, including cross section of the detector, and number of gamma rays likely to interact with the detector at its location relative to the source, and the number of probable reactions that would create the gamma rays. However, these should be the reference points, with extensive samples up to the same depth (within reason) that would produce gamma rays that would reach the detector as calibration points. Peak area analysis has proven itself to be a valuable tool in gamma ray spectrometry, in gamma rays that produce an identifiable peak, and particularly in regions with fewer interactions. This method should be used as a preliminary analysis on future BGO spectra, and used in conjunction with more sophisticated methods of analyzing gamma rays that do not produce an identifiable peak.
ACKNOWLEDGEMENTS

I would like to thank the NASA Space Grant Consortium at the University of Hawai‘i at Mānoa for this wonderful opportunity. Conducting, and presenting research has definitely helped me scholastically, and will continue to help me in the future in any career. Dr. Richard Starr for his help in IGOR and subroutines, Dr. Jeff Taylor for his support and help in identifying mare limits, and John Tirador for his help in manually adjusting backgrounds in IGOR. I’d like to thank Dr. Peter Englert, who made this project possible, introduced me to the field of gamma ray spectrometry, and supported and encouraged me to learn more about the things I was interested in. I will always be thankful.

REFERENCES


http://geo.pds.nasa.gov/missions/lunarp/level1.html


http://pds-geosciences.wustl.edu/missions/lunarp/reduced_special.html

Figure 4: Tranquillitatis map with Current Iron abundances below the pixel number and Calculated abundances above

Figure 5: Imbrium map with Current Iron abundances below the pixel number and calculated abundances above