2-P

X-641-72-351
PREPRINT

NASA TM X- 66068

LUNAR COMPOSITION FROM APOLLO ORBITAL MEASUREMENTS

ISIDORE ADLER
JACOB I. TROMBKA
LO I. YIN
PAUL GORENSTEIN
PAUL BJORKHOLM
JESSE GERALD

(NASA-TM-X-66068) LUNAR COMPOSITION FROM APOLLO ORBITAL MEASUREMENTS I. Adler, et al (NASA) Sep. 1972 52 p CSCL 03B
N73-10848
Unclas
G3/30 45690

SEPTEMBER 1972

GSFC — GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

LUNAR COMPOSITION FROM APOLLO ORBITAL MEASUREMENTS

Isidore Adler

Jacob I. Trombka

Lo I. Yin

Goddard Space Flight Center

Paul Gorenstein

Paul Bjorkholm

American Science & Engineering

Jesse Gerard

Eastman Kodak Research Laboratories

September 1972

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

LUNAR COMPOSITION FROM APOLLO ORBITAL MEASUREMENTS

ABSTRACT

Several spectrometers carried in the Service Module of the Apollo 15 and Apollo 16 spacecraft were employed for the compositional mapping of the lunar surface. The observations involved the measurements of secondary (fluorescent) X-rays, gamma-rays and alpha particle emissions. A large scale compositional map of over 20 percent of the lunar surface was obtained for the first time. It was possible to demonstrate interesting chemical differences between the mare and the highlands, to find specific areas of high radioactivity and to learn something about the composition of the moon's hidden side. Further the same devices were used to obtain useful astronomical data during the return to earth.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

LUNAR COMPOSITION FROM APOLLO ORBITAL MEASUREMENTS

INTRODUCTION

With Apollo 15 began a significant series of new experiments under the heading of Lunar Orbital Science. The Apollo Command-Service Module (CSM) was used for the first time to carry a large array of instruments for orbital surveys of a number of lunar characteristics. Sector 1 of the CSM, used heretofore to carry a third oxygen tank, was packed full of scientific instruments to map the moon from orbit simultaneously with the various surface activities of the Lunar Module crew. Fig. 1 shows the Science Instrument Module (SIM) and its instrumental complement. Carried in the SIM bay were eight experiments: an X-ray fluorescence spectrometer, a gamma-ray spectrometer, an alpha particle spectrometer, a panoramic camera, a laser altimeter, a mass spectrometer and a subsatellite (carrying three geophysical experiments) which was injected into lunar orbit.

Of the above experiments the X-ray, gamma-ray and alpha particle spectrometers were employed in obtaining chemical information about a large part of the moon's surface. The mass spectrometer was used for studying the moon's tenuous atmosphere at orbital altitudes. It is noteworthy that the X-ray and gamma-ray instruments were also used during the trans-earth coast for performing X and gamma-ray astronomy.

The X-ray, gamma-ray and alpha particle measurements which are the subject of this paper were the components of an integrated geochemistry

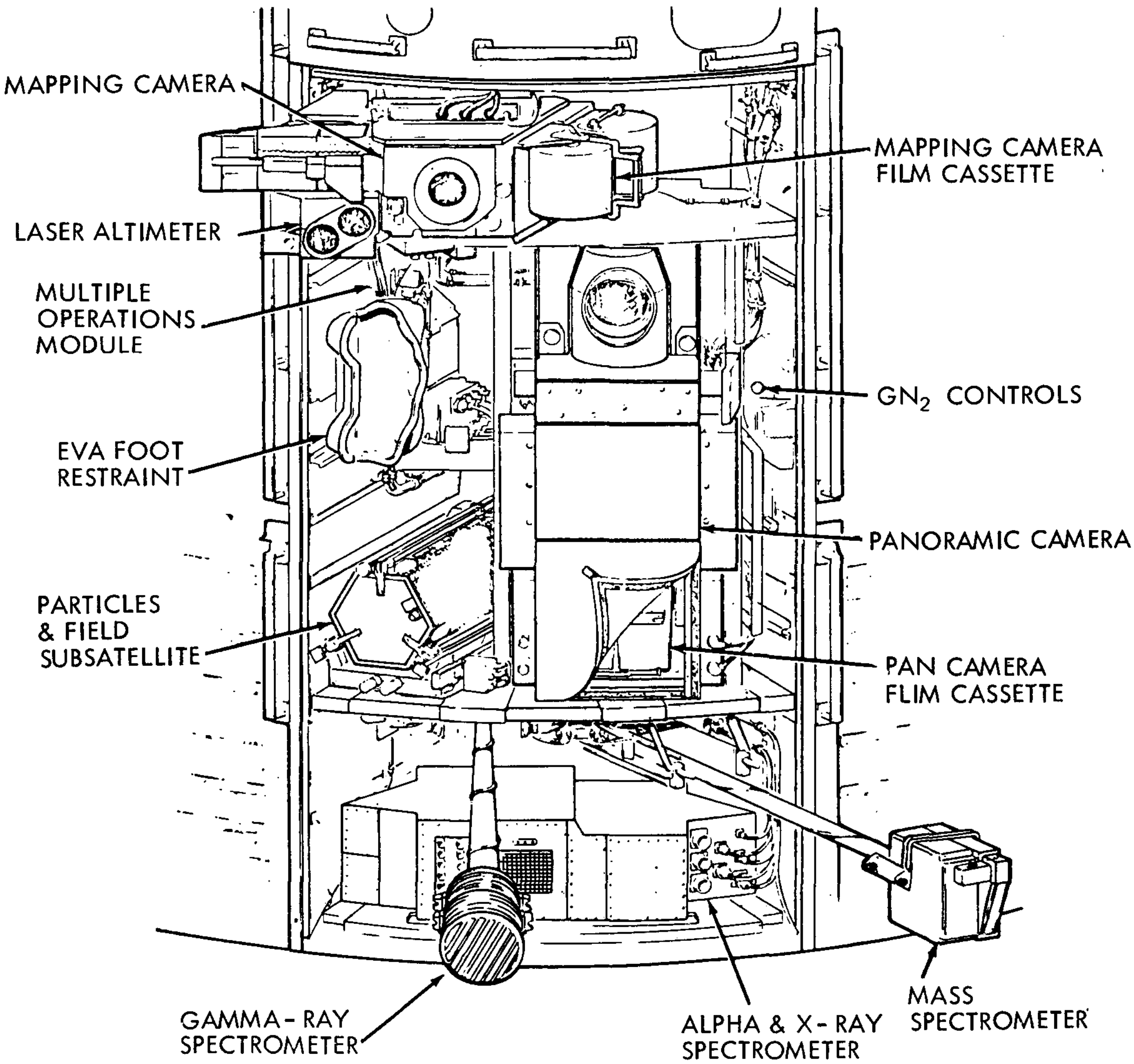


Figure 1. The Science Instrument Module (SIM) of the Apollo 15 and Apollo 16 Spacecraft. The various instruments and their position in the SIM bay are shown.

experiment. While each experiment was designed to measure different chemical elements, the information obtained was complementary in yielding more comprehensive information about the moon's chemistry.

Fig. 2 shows the SIM and the experiments as seen by the Apollo 15 surface crew on their way back from the lunar surface just prior to rendezvous. The X-ray, gamma-ray and alpha particle spectrometers are shown at the base of the SIM. The X-ray experiment is seen with its protective doors closed, a procedure that was always followed during maneuvers involving the small jets on either side of the SIM bay.

QUESTIONS ABOUT THE MOON

Prior to 1960 our knowledge about the moon came from earth-based telescopic studies. In the last decade however, numerous programs initiated by the United States and the Soviet Union have provided us with a great deal of new information. The programs have included such varied efforts as the Ranger series flybys, Surveyor landers, Lunas, Orbiters, Apollo and Lunakhod flights. The first in-situ chemical analysis of lunar surface material came during the Surveyor program; Surveyor 5 landed at Mare Tranquilitatis; Surveyor 6 at Sinus Medii and Surveyor 7 on the rim of the very large crater Tycho. The first reasonably successful attempt at orbital analysis was performed by the Russian Luna 10(1), orbiting the moon and carrying a gamma-ray spectrometer. The analysis of the gamma-ray spectrum from the lunar surface showed that K, U and Th were comparable to those in terrestrial basalts and inconsistent with

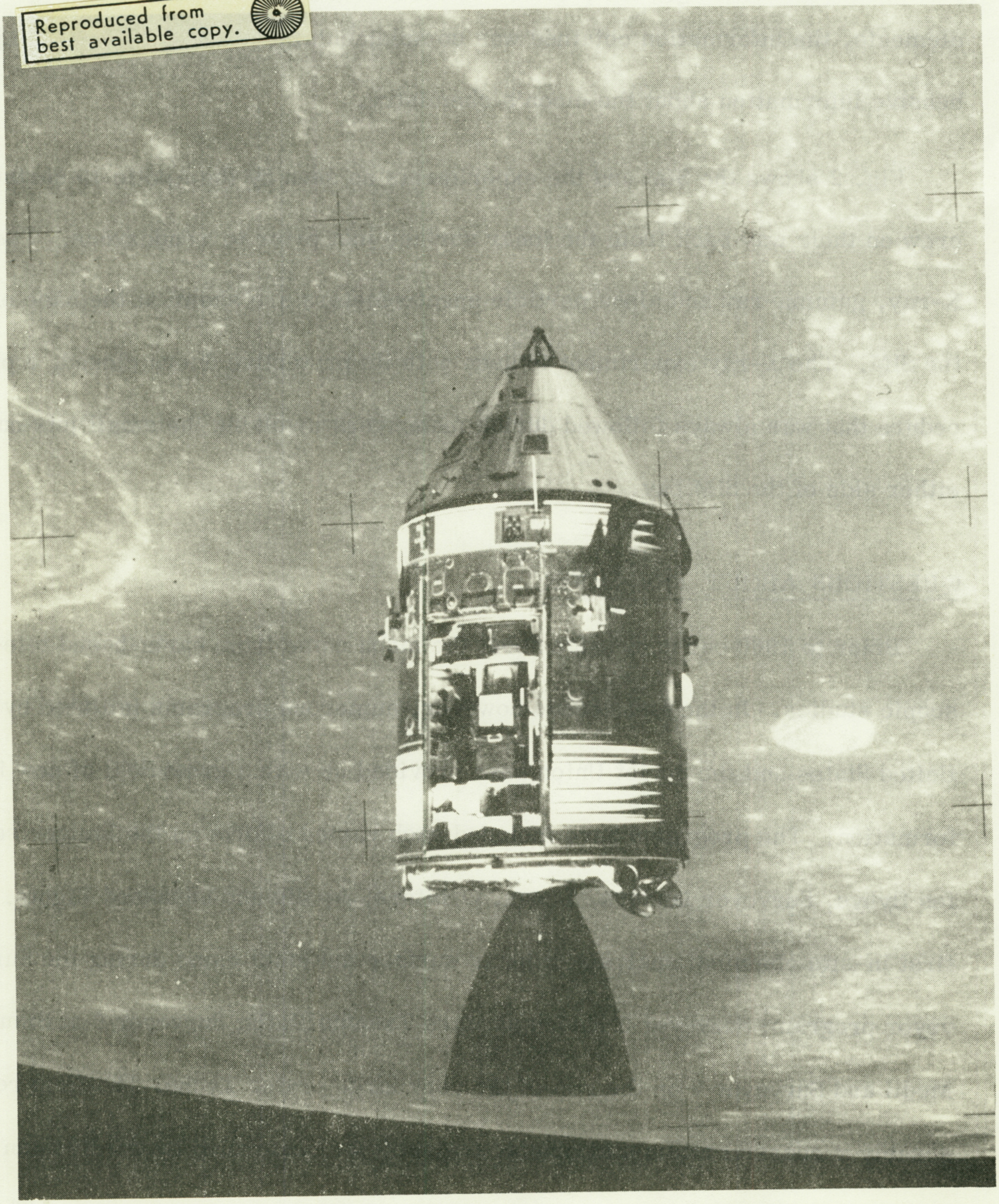


Figure 2. The Command and Service Modules in lunar orbit as seen from the LM. The lunar surface is seen below and there is an excellent view of the SIM showing the scientific experiments. Astronaut A. Worden was the Command Module pilot; J. B. Irwin, the Lunar Module pilot and D. R. Scott, commander.

such compositons as granites, ultra-basic rocks or chondrites. A similar conclusion was reached by the Surveyor investigators (2) who proposed that the maria were similar but not identical in chemical composition and the highlands although related were clearly lower in iron concentration and higher in aluminum i.e. more feldspathic.

In 1969 Apollo 11 landed men on the moon for the first time; the site Mare Tranquilitatis. The astronauts brought back a number of samples, a historic event, placing at the disposal of scientists, carefully collected samples from another body in our solar system. The samples, a collection of crystalline rocks, breccias and soils were essentially basalts. In the soils, however, were small fragments of rock which were obviously not indigenous to the mare site but appeared to come from elsewhere, perhaps the highlands. These were feldspathic rocks ranging from gabbroic anorthosites through anorthositic gabbros to anorthosite. The gabbroic anorthosites seemed to be similar in composition to the analysis reported by Surveyor 7 as a result of its flight to the Tycho highlands.

The Apollo 12 flight was also noteworthy in returning still another type of rock euphemistically named "KREEP", a rock enriched in K, rare earths, phosphorus and the radioactive elements Th and U. With Apollo 14 to the Fra Mauro area came an attempt to sample rocks associated with a major cratering event; the production of the enormous Imbrium basin. These rocks proved to be mainly breccias with compositions closely allied to the Kreep type rocks described above and coming quite possibly from deeper layers within the moon. This brings us to the Apollo 15 and 16 missions.

From the above brief review it is obvious that our knowledge of the moon has come from samples collected at a few chosen areas of the moon and our view of the total moon as extrapolations from the newly acquired facts. As pointed out by Lowman (3) "the analysis of these returned lunar samples had begun to fill two major gaps in our knowledge: the absolute ages of the lunar geologic time scale and resonably firm speculation about the composition and origin of the main lunar rock types". However there were many good reasons for seeking chemical information from other lunar sites (many of which will be inacessible to manned landings for years to come). Certainly a global compositional map would be of inestimable value in helping us to understand the moon. With these considerations in mind, a combined geochemical experiment was proposed as a collaborative effort involving scientists from several institutions: Goddard Space Flight Center; The University of California, San Diego; The Jet Propulsion Laboratory; and American Science and Engineering. The experiments were then implemented and flown on both Apollo 15 and Apollo 16. As we will show below these experiments have helped considerably in answering a number of questions relating to the early history and origin of the moon.

ORBITAL REMOTE SENSING

There are only a limited number of observational phenomena from which one can infer unique elemental identifications and concentration. A survey of the electromagnetic and particulate spectra shows only a few possibilities. Furthermore it is obvious that none can yield results precise by laboratory standards. Nevertheless, such experiments as gamma-ray, or X-ray spectroscopy can provide a great deal of useful information.

The earliest American attempts at performing gamma-ray spectroscopy of the moon were made in connection with the Ranger 3, 4 and 5 flyby flights. Gamma-ray experiments were also carried aboard the Russian Luna 10 and 11 spacecraft which were placed in orbit around the moon.

The first approach to measuring fluorescent X-rays from the lunar surface was made by Mandel'shtam et. al. (4) from the orbiting Luna 12 spacecraft. Several small geiger counters having a band pass between 8-12 Å were flown which alternately looked at the lunar surface and then out into space for comparison. Although little or no compositional data were obtained, there were some positive indications that the sun does in fact, produce measureable fluorescent X-rays from the lunar surface.

RADIATION ENVIRONMENT AT THE LUNAR SURFACE

Fig. 3 summarizes our view of the radiation environment at the lunar surface. The orbital experiments to be described here were based on this view of the radiation environment. Both natural and induced sources of radiation are present. Among the principal naturally occurring radioactive constituents are the long lived nuclides ^{40}K, ^{238}U, ^{232}Th and their decay products. These

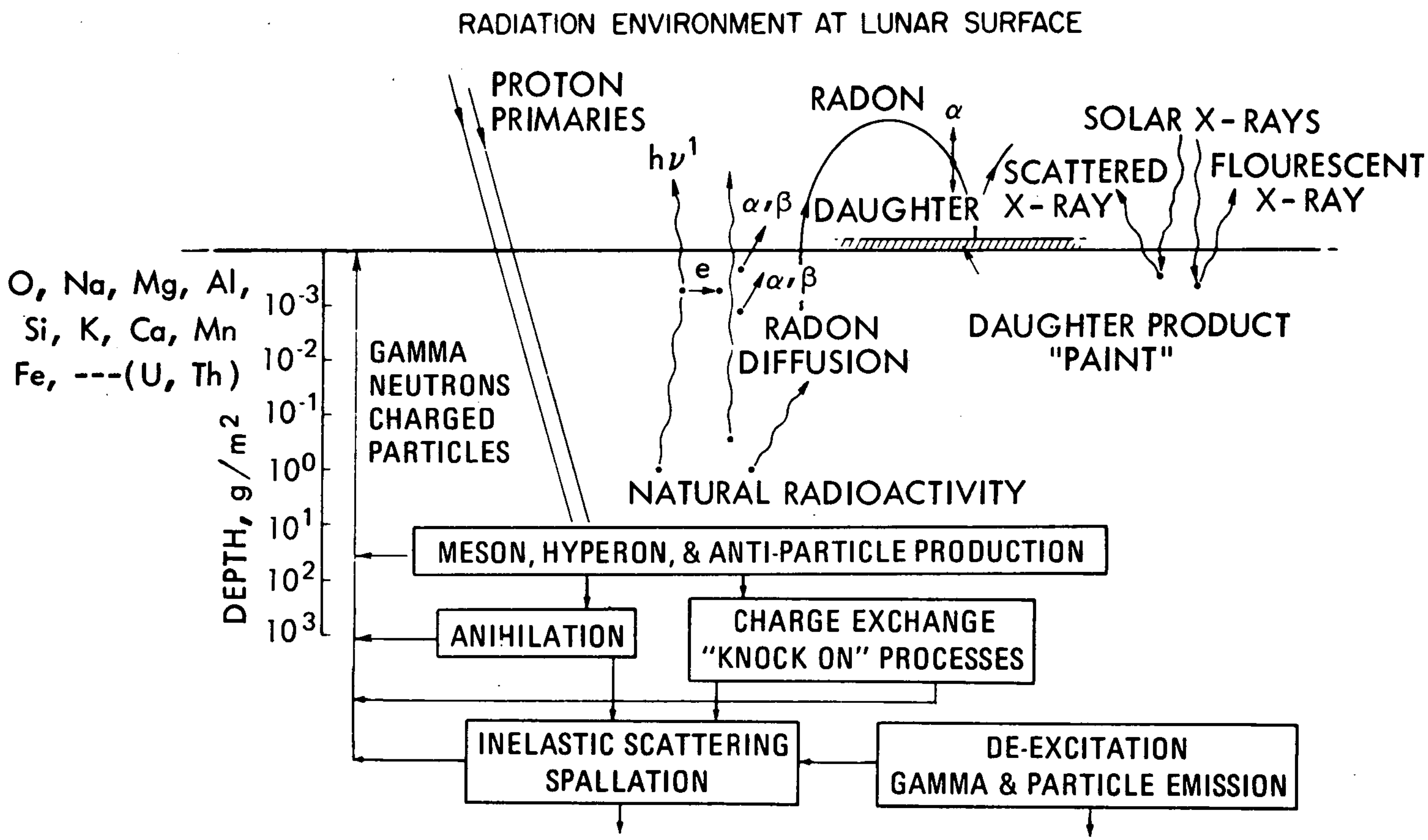


Figure 3. A Summary of the Radiation Environment at the Lunar Surface

sources emit alpha, beta and gamma radiation of various energies. Special processes such as radon diffusion(5) may also occur. Bombardment of the lunar surface by cosmic rays and energetic solar protons also produce a variety of shorter lived nuclides and as a result, induced radioactivity, Cosmic ray interactions with the lunar surface will also produce a prompt emission of charged particles, neutrons and photons.

Solar X-rays absorbed in the lunar surface produce fluorescent X-rays characteristics of some of the elements making up the lunar surface. The relative yields of these X-rays depends on the intensity and spectral character of the solar X-ray flux as well as the relative abundance of the elements. Fig. 3 also shows that radon and thoron diffusion to the lunar surface would be expected to produce alpha particles characteristic of the various decay processes. These various phenomena will be discussed in greater detail below.

GAMMA-RAY EXPERIMENT

From the very beginning of the planning for lunar exploration, it was assumed the K, U and Th would be among the key elements to an understanding of lunar evolution. In terrestrial processes the decay of these elements is considered to be the source of the energy leading to volcanism and magmatic differentiation; and in turn, the concentration of these elements becomes a measure of the extent of chemical differentiation (K, U and Th tend to concentrate in the late stage crystalline rocks such as granites). By Apollo 15 excellent determinations of K, U and Th had been made on the various returned samples from the

Apollo 11, 12 and 14 missions. These are summed up in Fig. 4 where K vs. U values have been plotted for various lunar materials. For comparison, a line is drawn for terrestrial materials ranging from basalts to granites. The relative position of achondrites is also shown. The diagonals represent K/U ratios. It is obvious that the lunar materials have lower K/U ratios than the terrestrial magmatic rocks, essentially because of the higher U and lower K values. A similar situation (not shown here) also exists for the K/Th ratios. Furthermore, there is a distinct variation from one lunar site to the next. Because K, U and Th are such important indicators of geochemical processes, the attempt to map these elements globally around the moon is obviously of great importance.

In addition to the gamma-rays from the naturally occurring nuclides, gamma-rays are also produced by cosmic ray interactions. Strongly interacting particles constantly bombard the lunar surface. The greatest proportion of these are solar protons, although there is a galactic component from outside the solar system. The situation on the moon is unique relative to the earth. Because of the absence of an atmosphere and the low magnetic fields, the charged particles are not appreciably deflected and thus, strong interactions between the particles and lunar surface occur. These interactions are varied and complex including such effects as meson production, "knock-on phenomena" and evaporation mechanisms. Inelastic processes produce excited nuclei which emit gamma-rays, charged particles and neutrons. These reactions can be expected to produce a spectral distribution of gamma-rays containing a number of lines characteristic

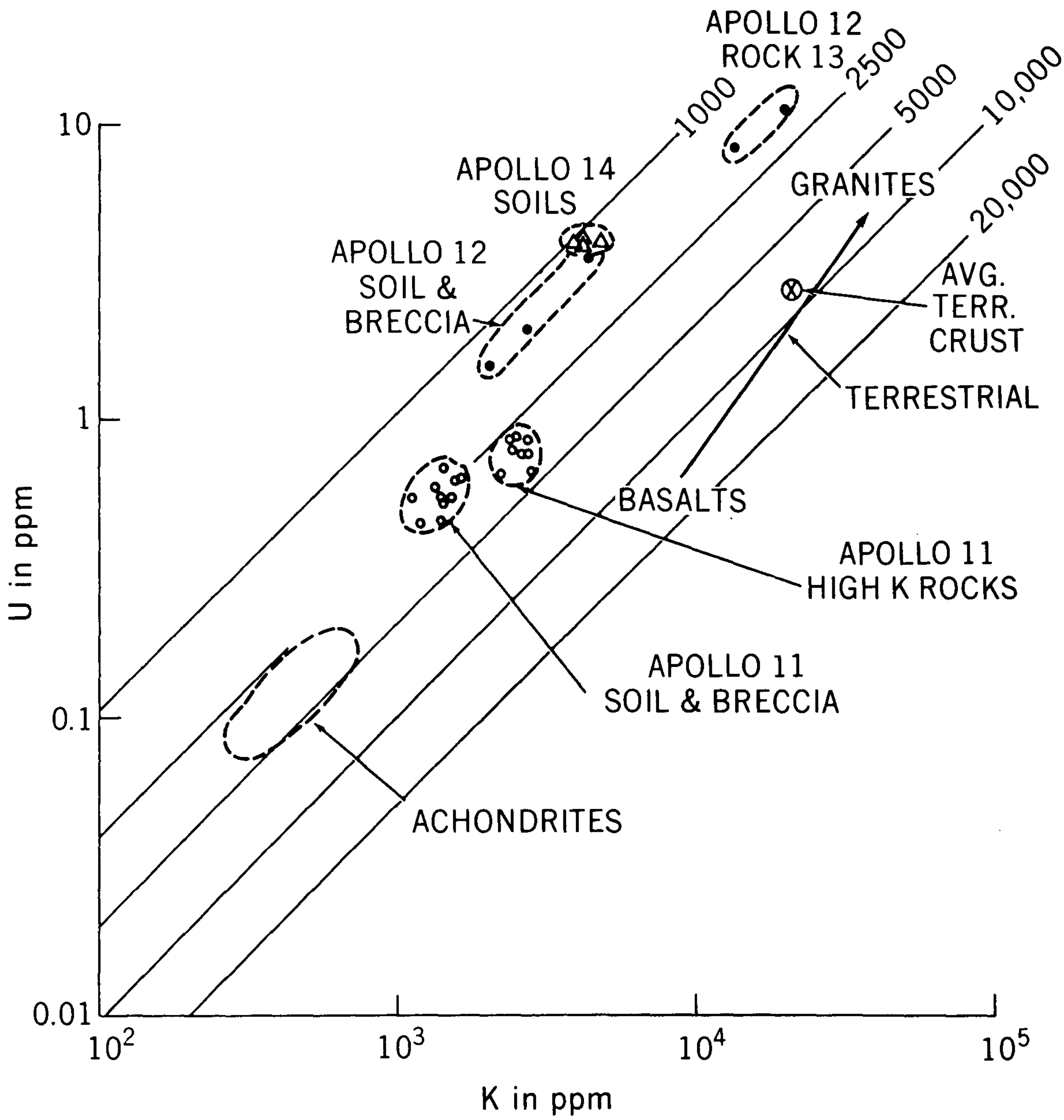


Figure 4. Uranium vs. potassium in various lunar and terrestrial materials. For Comparison, a line is drawn for terrestrial materials ranging from basalts to granites.

of the elements in the lunar surface. It has been possible in fact, to calculate expected spectra for typical lunar materials, assuming a scintillation crystal of the size actually flown(6). These theoretical spectra show a large number of useful characteristic lines superimposed on a continuum.

The gamma-ray sensing assembly flown on Apollo 15 and Apollo 16 was composed of three major subassemblies: the electronics, the scintillation detector and the thermal shield. A partial view in cross section is shown in Fig. 5. In flight the gamm-ray spectrometer was deployed at the end of a 7.5 meter boom in order to remove it as far as possible from both the natural radioactivity and the activity induced in the spacecraft by the ambient cosmic ray flux. Because it was important to know the extent of the vehicle contributed background, the boom was deployed during the trans-earth coast to intermediate distances of 2.5 and 4.5 meters. Background measurements were made with the experiment in stowed position and at the 2.5 and 4.5 meter distances. The detector (Fig. 5) consisted of a right cylindrical NaI (thallium activated) crystal, about 7 cm x 7 cm. The crystal had a thin mantle of a scintillating plastic crystal. The mantle scintillator was optically isolated from the primary NaI crystal and both detectors were used in anti-coincidence. The primary detector had approximately 8.5% and 7.5% resolution for the 0.661 MeV line of ^{137}Cs respectively during the Apollo 15 and 16 missions. The plastic scintillator was used to eliminate the effects of charged-particle cosmic-ray flux within the field of view of the detector.

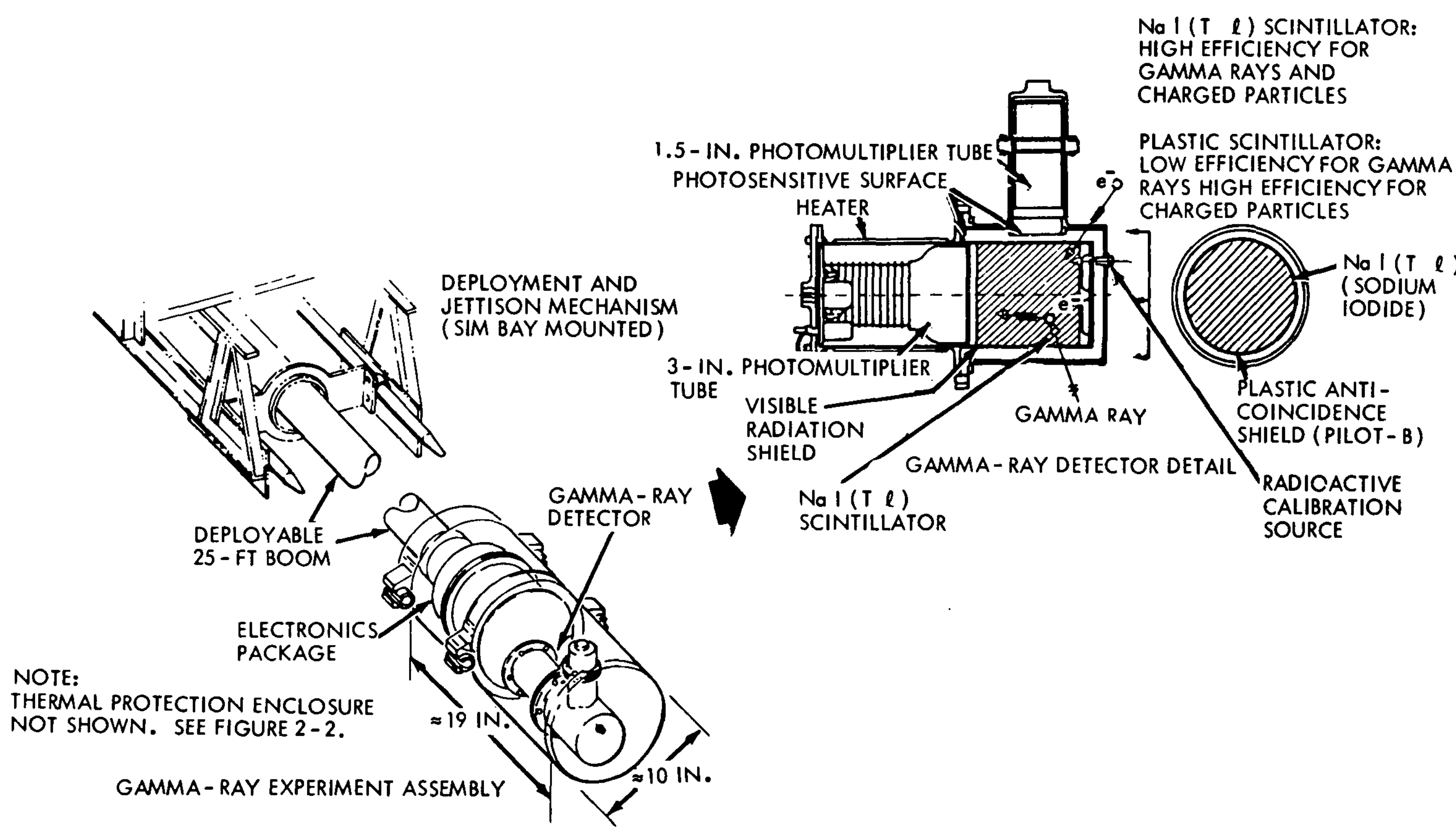


Figure 5. Gamma-ray Detector Detail

The electronics consisted of a 512 channel analog to digital converter built around a 2-MHz oscillator. In flight, data were transmitted channel by channel in real time during earth contact and stored on tape for subsequent telemetry when out of line of sight.

LUNAR X-RAY FLUORESCENCE EXPERIMENT

The basis for the orbital X-ray experiment is that characteristic X-rays follow the interaction of solar X-rays with the lunar surface. The results of numerous calculations had indicated that the typical "quiet" solar X-ray spectrum was energetically capable of producing measureable amounts of characteristic X-rays from all the abundant elements with atomic numbers of approximately 14(Si) or smaller. During brief periods of more intense solar activity it was expected that characteristic X-rays from higher atomic number elements would also appear.

A study of the quiet-sun solar X-ray flux, with low resolution instruments such as proportional counters, reveals a spectral distribution that decreases very sharply with increasing X-ray energies. If a strictly thermal mechanism of production is assumed, variable coronal temperatures are calculated which range between 10^6 and 10^7 °K. Variations in temperature produce changes in both flux and spectral composition. From our knowledge of the process of fluorescent X-ray production we must therefore expect a variation in X-ray fluorescent intensities and also in the relative intensities from the various elements observed in the lunar surface. For example, if the solar spectrum hardens (increased fluxes of higher energy), an enhancement of the intensities from the heavier elements relative to the lighter ones would be observed.

An X-ray monitor was therefore employed during the mission to follow the possible variation in solar X-ray intensity and spectral shape. In addition, detailed simultaneous measurements of the solar X-ray spectrum were obtained during the mission from the various Explorer satellites that monitor solar radiation.

A simplified estimate of the emitted solar X-ray flux based on Solrad(7) observations is shown in Fig. 6. This follows from combining a coronal temperature of 1.5×10^6 °K with a hot spot temperature of about 3×10^6 °K in proportions determined by the Solrad data and using the model developed by Tucker and Koren(8). Superimposed on this curve along the energy axis are the K shell absorption edges for Na, Mg, Al, Si and K. Only the solar X-rays with energies on the high side of the absorption edges are capable of exciting these elements and to a degree which depends on the incident flux and the ionization cross-sections. Thus, under quiet sun conditions, the solar flux is most suitable for exciting the light elements, including the major, rock forming elements Si, Al and Mg.

Calculations of expected characteristic X-ray yields had been made by Gorenstein et. al.(9) and Eller(10) based on an assumed temperature 4×10^6 °K for the 1-8 Å region and a solar free-free mechanism.

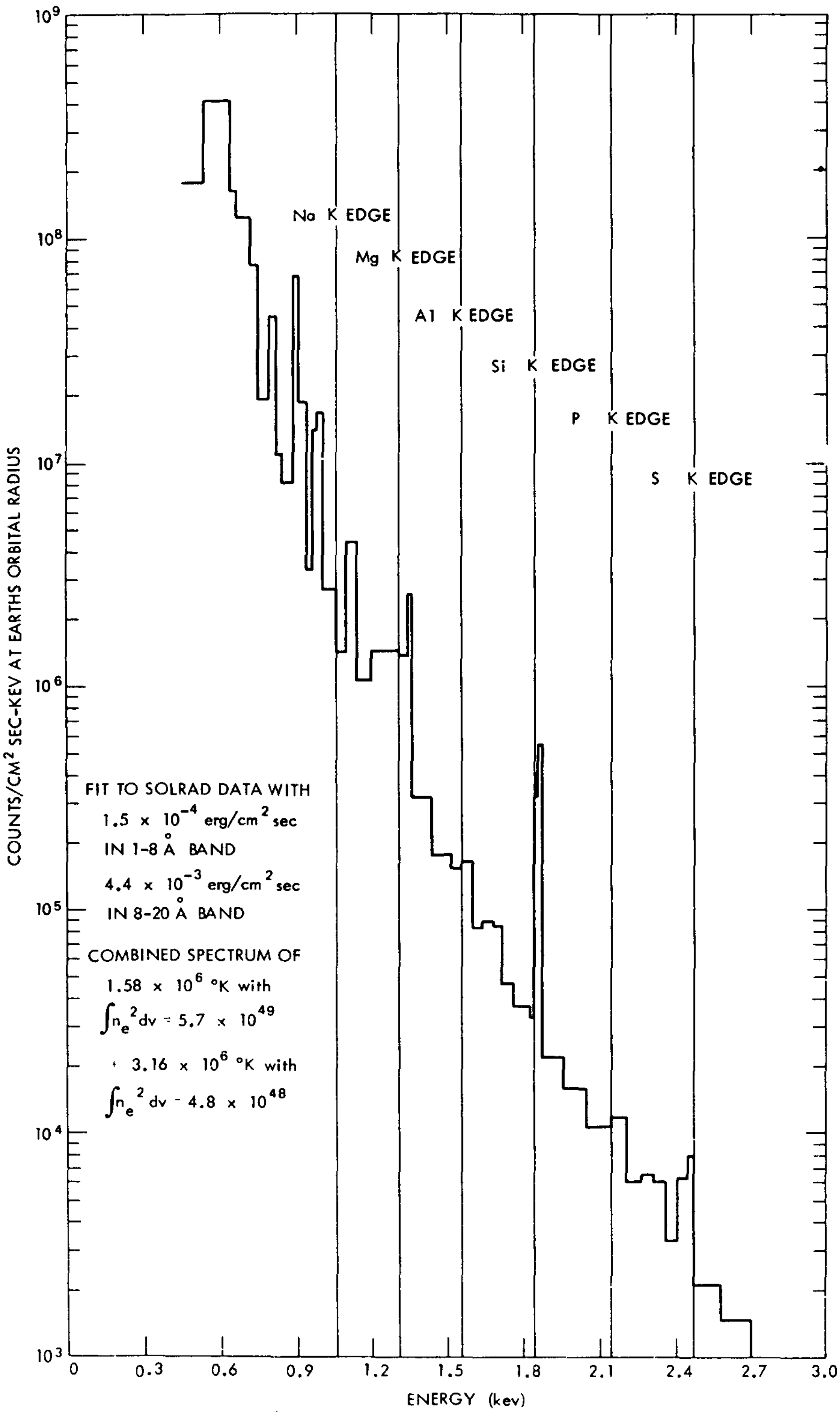


Figure 6. A simplified estimate of emitted solar X-ray flux based on Solrad data and the model developed by Tucker and Thoren (8). Superimposed are the absorption edge positions for a number of elements.

Because of the low value of the lunar X-ray brightness it was obvious that high resolution devices such as crystal spectrometers with their low inherent efficiency were not feasible. In order to obtain adequate counting statistics it was necessary to design around large area proportional counters. Further, because of the low X-ray energies, the windows were thin and highly transmitting.

The X-ray fluorescence sensing assembly consisted of three gas filled (P-10) proportional counters, mechanical collimators, calibration sources for in-flight calibration, a temperature monitor and associated electronics. The individual detectors where each approximately $30\,cm^2$ in area and had 3.8×10^{-2} mm beryllium windows.

Two methods for energy resolution were employed. The output of the detectors was energy analyzed by eight discriminator channels covering in equal intervals 0.5 to 2.75 KeV in high gain mode of 1-5.5 KeV in the low gain mode. As an additional method of energy discrimination one detector was operated bare and the other two had selected X-ray filters. A magnesium foil filter covered one window and the other had an aluminum foil filter. The magnesium filter preferrentially filters the aluminum and silicon radiation while the aluminum filter is most selective for the silicon radiation. Fig. 7 shows the X-ray assembly mounted in the same enclosure that houses the alpha particle spectrometer (described below). The nature of the detector configuration provided a nominal 60° field of view. At the mission altitude of nearly 110 km this permitted an instantaneous view of an area approximately 110 km on edge.

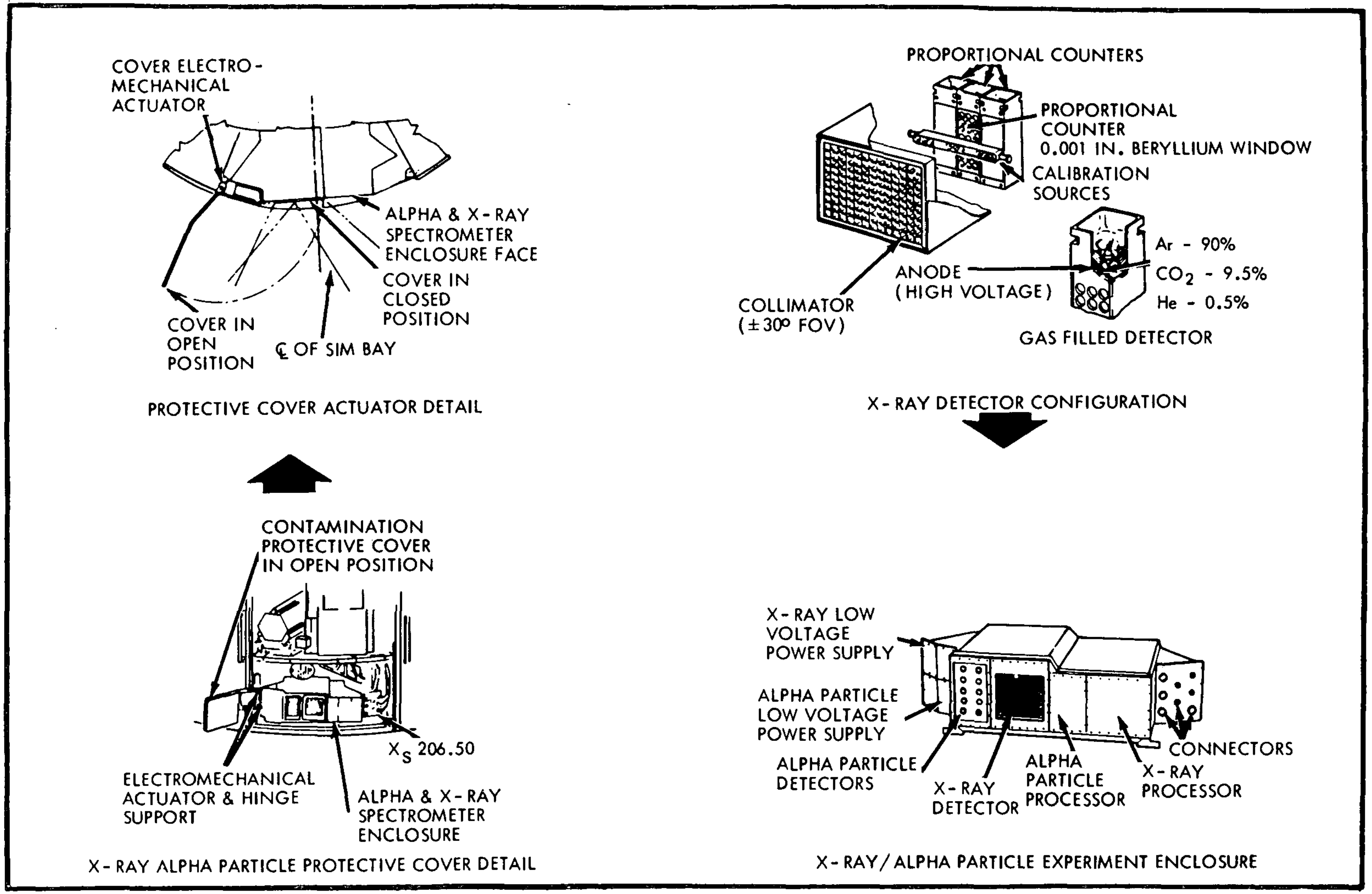


Figure 7. Details of the X-ray Fluorescence Experiment

The X-ray processing electronics assembly was unique in that it not only discriminated against pulses of different amplitudes but among pulse shapes as well. Thus the processing of the X-ray pulses from the detectors rejected non-X-ray events that produced pulses of a different shape. This mode of operation gives a considerable improvement in signal-to-noise ratios under circumstances where gamma-ray and cosmic-rays produce unwanted background. The output of each detector was fed to an eight channel energy analyzer. The counts were stored in registers for 8 sec. intervals, and then the outputs transferred as binary coded information to telemetry. Backside data were stored on tape and transmitted when the spacecraft was within line of sight of the earth.

ALPHA PARTICLE EXPERIMENT

There are a number of possible sources for alpha particles from the lunar surface. These are: the alpha-radioactive decay of radon and thoron (and their daughter products) which have diffused out of the first few meters of lunar soil; the alpha radioactivity produced by the interaction of galactic cosmic rays with the lunar surface materials; and the evaporation of protons and alpha particles during solar flares, as a consequence of the interaction of flare associated energetic solar protons and alpha particles with the nuclei of lunar surface elements.

The most interesting phenomenon to investigate was the possible diffusion of radon and thoron. Kraner et. al. (5) had proposed a mechanism for the diffusion of radon and thoron through the upper surface layer of the moon and the subsequent "painting" of the surface by radioactive radon and thoron decay products. Some part of the radon and thoron produced by radioactive decay was postulated as escaping from the host minerals into the interstitial voids in the soil and then diffusing through these voids to the surface; the rate of diffusion being related to the diffusion coefficients and soil porosity. If thermal velocities were assumed for the emerging radon and thoron, then nearly all the molecules would be trapped in the moon's gravitational field. Radon with its 3.8 day half life should travel a considerable distance before undergoing decay. Thoron, on the other hand, with a 55 second half life, would be expected to decay near its source. Both of these species would yield daughter products giving characteristic spectral lines. Thus the detection of this phenomenon could be an important indicator of active regions (volcanism) leading to emanation from the lunar surface.

The necessary equipment for alpha-particle measurements (Figs. 7 and 8) is basically simple. The detectors are solid state, surface barrier types. The flight instrument consisted of an alpha detector assembly and alpha processing electronics. The alpha detector assembly contained ten surface barrier sensors to convert incident alpha particles into electrical pulses suitable for processing by the electronics assembly. All the sensors accepted particles of the same energy range. The processing assembly took the output of the detectors, analyzed the first acceptable pulse in each 100-msec telemetry interval and produced an eight-bit binary code proportional to the pulse amplitude on eight

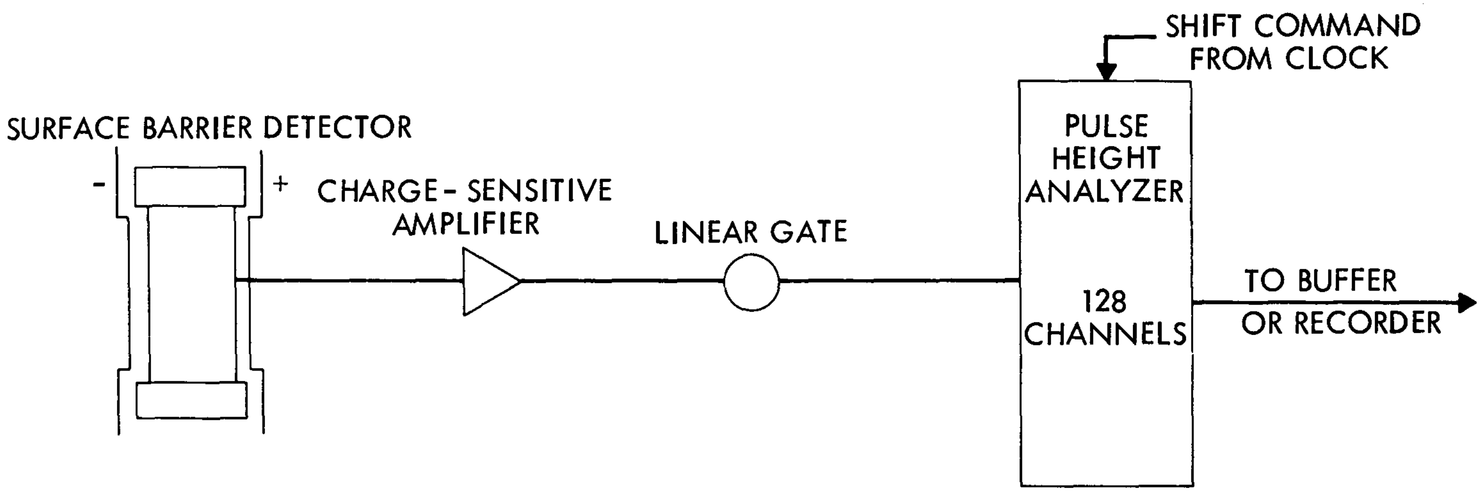


Figure 8. Measurement System for the Alpha-Particle Experiment

parallel telemetry inputs. An analog output identified the sensor in which conversion occurred.

RESULTS OF THE ORBITAL GEOCHEMISTRY MEASUREMENTS

In the following sections we shall report on the results of the X-ray, gamma-ray and alpha particle experiments for both the Apollo 15 and 16 flights. The X-ray data which were most rapidly reduced will be presented first. The gamma-ray data are being actively analyzed and have begun to yield a very interesting picture of the surface distribution of the radioactive elements. The alpha particle data have also been reduced and will be discussed although the results are somewhat more ambiguous.

The Apollo 15 mission was targeted for the Hadley Rille region while the Apollo 16 flight objective was the Descartes region. The Apollo 15 flight was at an orbital inclination of 26 deg. as compared to 9 deg. inclination of the Apollo 16 flight. As a consequence, the 15 ground track covered a larger projected area than the 16 flight. In considering the X-ray experiment one must bear in mind that the observations include only that part of the moon that was illuminated by the sun. By contrast the gamma-ray results come from a band around the entire moon. There was some overlap of coverage between the Apollo 15 and 16 missions which permitted a comparison of results for both flights. As we will see the results compared closely enough so that no normalization was required. The total coverage for the two missions when combined was about 20 percent of the moon's surface. The Apollo 15 flight covered such areas as the craters Gagarin, Tsiolkovsky, the far side and eastern limb highlands, the maria such as Smythii, Crisium, Fecunditatis, Tranquilitatis, Serenitatis, Imbrium, Oceanus Procellarum, the Haemus mts., and the Apennines. To this the Apollo 16 added such features as Mare Cognitum, Mare Nubium, Ptolemaeus, the Descartes region and Mendeleev (see Fig. 10).

TREATMENT OF THE DATA

The data from the X-ray experiment were displayed in almost real time as a numeric readout on a cathode ray tube monitor. The data appeared in the form of a running sum for the eight energy channels for each of the four detectors (the fourth detector was the solar monitor). The actual prime data was recorded on tapes and ultimately processed. These were taken at 8 second intervals. Thus, taking into account the spacecraft motion, the minimum surface resolution element, based on our nominal field of view (60 deg.), was about 110 x 150 km. A typical example of the nature of the raw data is shown as a histogram in Fig. 9.

The data were initially reduced to Al/Si and Mg/Si intensity ratios. Ultimately these values were converted to chemical ratios. The procedures for doing this have been described in detail elsewhere (11). In general by using three detectors with varying X-ray response (see description of experiment), one can write three simultaneous equations and solve them by a least squares matrix inversion for the observed intensities. From these the contributions of the Si, Al and Mg can be inferred. The use of intensity ratios tends to minimize the effects of excitation, surface composition and terrain.

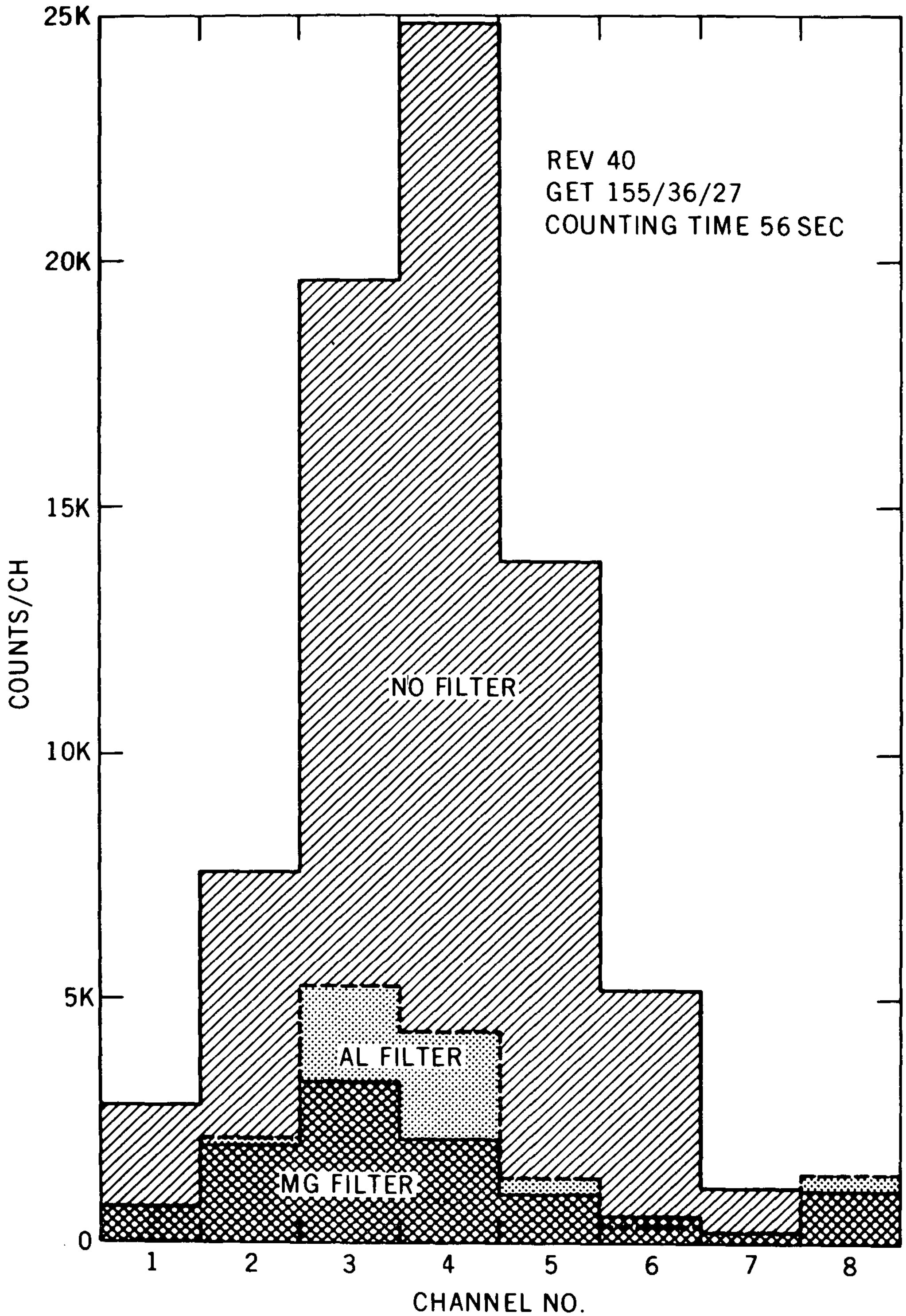


Figure 9. A Typical X-ray Spectrum for the Three X-ray Detectors Taken at the Subsolar Point

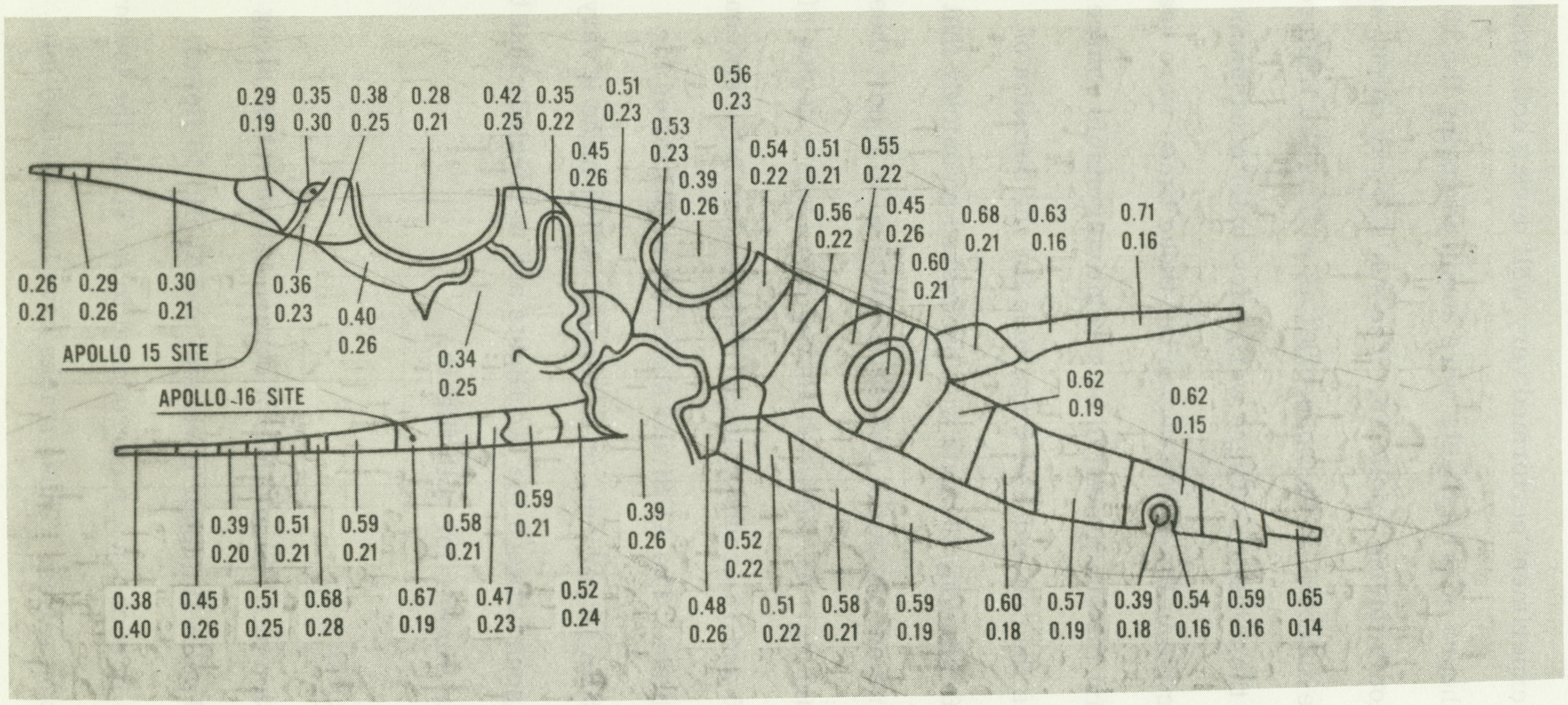


Figure 10. Variation of Al/Si and Mg/Si concentration ratios along the projected ground tracks for Apollo 15 (upper envelope) and Apollo 16 (lower envelope). The upper values in each square correspond to Al/Si and the lower numbers to Mg/Si.

OPERATION OF THE X-RAY FLUORESCENCE EXPERIMENT

The X-ray fluorescence experiment performed very well during both Apollo 15 and 16 flights. Some 100 hours of orbital data were acquired during the 15 flight and approximately 60 hours during Apollo 16. The sun's X-ray output was monitored continuously by the detector on the spacecraft as well as the Explorer satellites aloft at the time of the mission. There were a few brief occassions when the sun became more active in the X-ray region but these times were readily identifiable. For most part the sun proved to be a relatively stable source, the X-ray flux varying by less than an order of magnitude for the duration of both missions. During the 16 mission, the data was processed so quickly that it was possible to draw conclusions about the Descartes site and to report these to the crew working on the surface. As indicated above, there was a region of overlap between the Apollo 15 and 16 ground tracks. This was mainly between 50 and 100 degrees east longitude. The Al/Si and Mg/Si chemical ratios for both flights agreed to better than 10 percent, an agreement which made it very encouraging to draw comparisons between the two flights and to conclude that the sun's X-ray activity was quite similar for both flights.

RESULTS AND OBSERVATIONS

Fig. 10 shows the variation of Al/Si and Mg/Si concentration ratios along projected ground tracks for Apollo 15 (upper envelope) and Apollo 16 (lower envelope). The upper values in each square correspond to Al/Si and the lower numbers to Mg/Si concentration ratios. These tracks have been divided into areas based in part on obvious geologic features and in part on concentration contours. These relationships for Al/Si are shown in greater detail in Figs. 11 and 12 for the various features overflown. The ratios for various analyzed materials are shown along the right hand axis for reference. A number of observations can be drawn from a study of these figures:

a. The Al/Si ratios are highest in the highlands and considerably lower in the mare areas. The extreme variation is about a factor of two. The Mg/Si concentration ratios generally show the opposite relationship.

b. There is a general tendency for the Al/Si values to increase from the western mare areas to the eastern limb highlands.

c. There are distinct chemical contrasts between such features as the small mare basins and the highland rims (note for example the crater Tsiolkovsky in Fig. 11). The rim areas as one would expect are intermediate between the mare areas and the surrounding highlands.

Another interesting study involves a comparison of Al/Si intensity ratios versus the optical albedo values. These observations are particularly significant in view of the longstanding discussions about whether these albedo differences are solely representative of topographic differences or also a reflection of compositional differences among surface materials. Early workers such as Whitaker (12) and others recognized convincing evidence for compositional changes where sharp albedo changes occur. However, it remained for the later

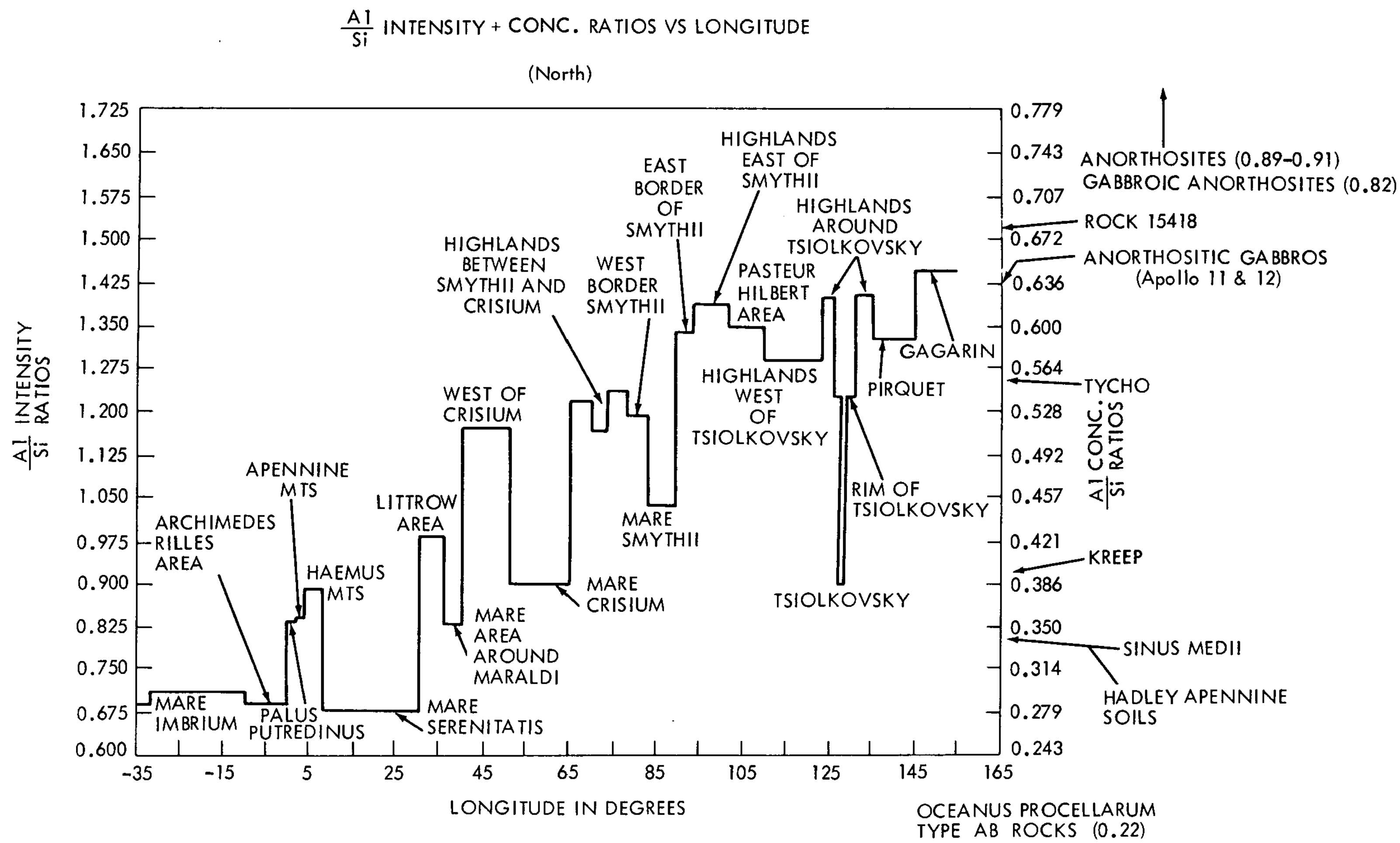


Figure 11. Al/Si ratios vs. longitude for the Apollo 15 ground track. The values for some reference materials are indicated on the right hand axis.

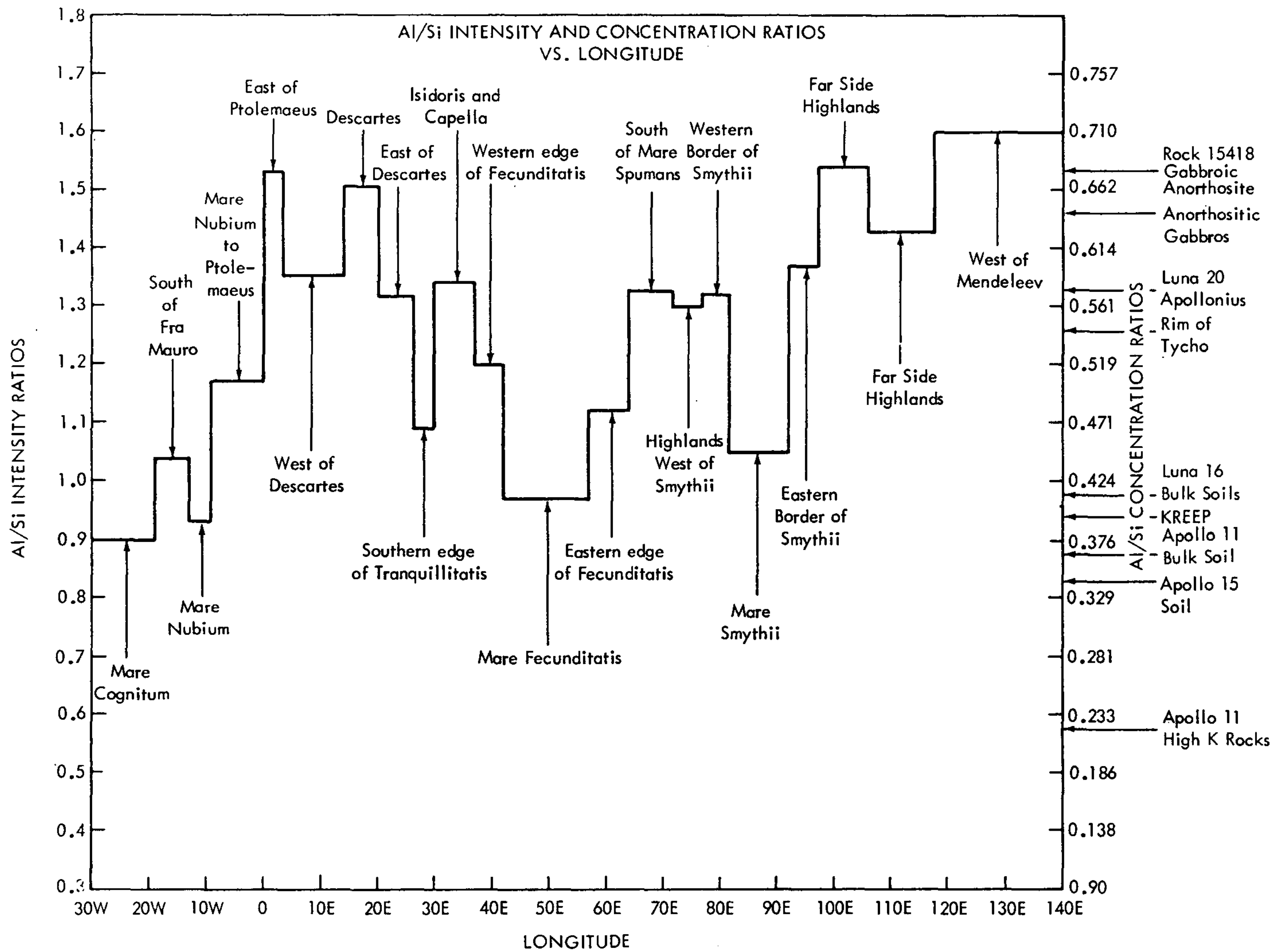


Figure 12. Al/Si ratios vs. longitude for the Apollo 16 ground track. The values for some reference materials are indicated on the right hand axis.

Surveyor, Apollo Luna and Lunakhod missions to provide quantitative compositional data. Chemical differences related to albedo were first confirmed by the Alpha Scattering Experiment carried on Surveyors 5, 6 and 7. Surveyors 5 and 6 analyzed widely separated mare sites and reported chemically similar surface materials for each. Surveyor 7, on the other hand, analyzed a highland site finding significant chemical differences between it and the two mare locations. The Surveyor results and the analyses of returned lunar samples confirmed that the albedo is indeed affected by composition as well as topographic differences. The X-ray fluorescence experiment on Apollo 15 and 16 has now provided the means to correlate regional albedo with surface composition (for selected chemical elements).

The data from both Apollo flights showed an excellent correspondence between Al/Si values and the optical albedo values. An example from the Apollo 16 flight is shown in Fig. 13. There is a positive correlation between the albedo and the Al/Si although the rate of change is not always similar. In the Apollo 15 plots the main anomalies were observed where an occasional small Copernican type crater occurred, and produced an abnormally high albedo value. This was considered to be due to the highly-reflective, finely divided ejecta rather than to compositional changes. A similar anomaly is noted in the Apollo 16 data around 27 deg. west longitude in a Tranquilitatis embayment north of Theophilus. Four Apollo 16 orbits are plotted. Orbits 58 and 60 show the expected decrease in Al/Si with decreasing albedo. Orbits 55 and 59 on the other hand, show an

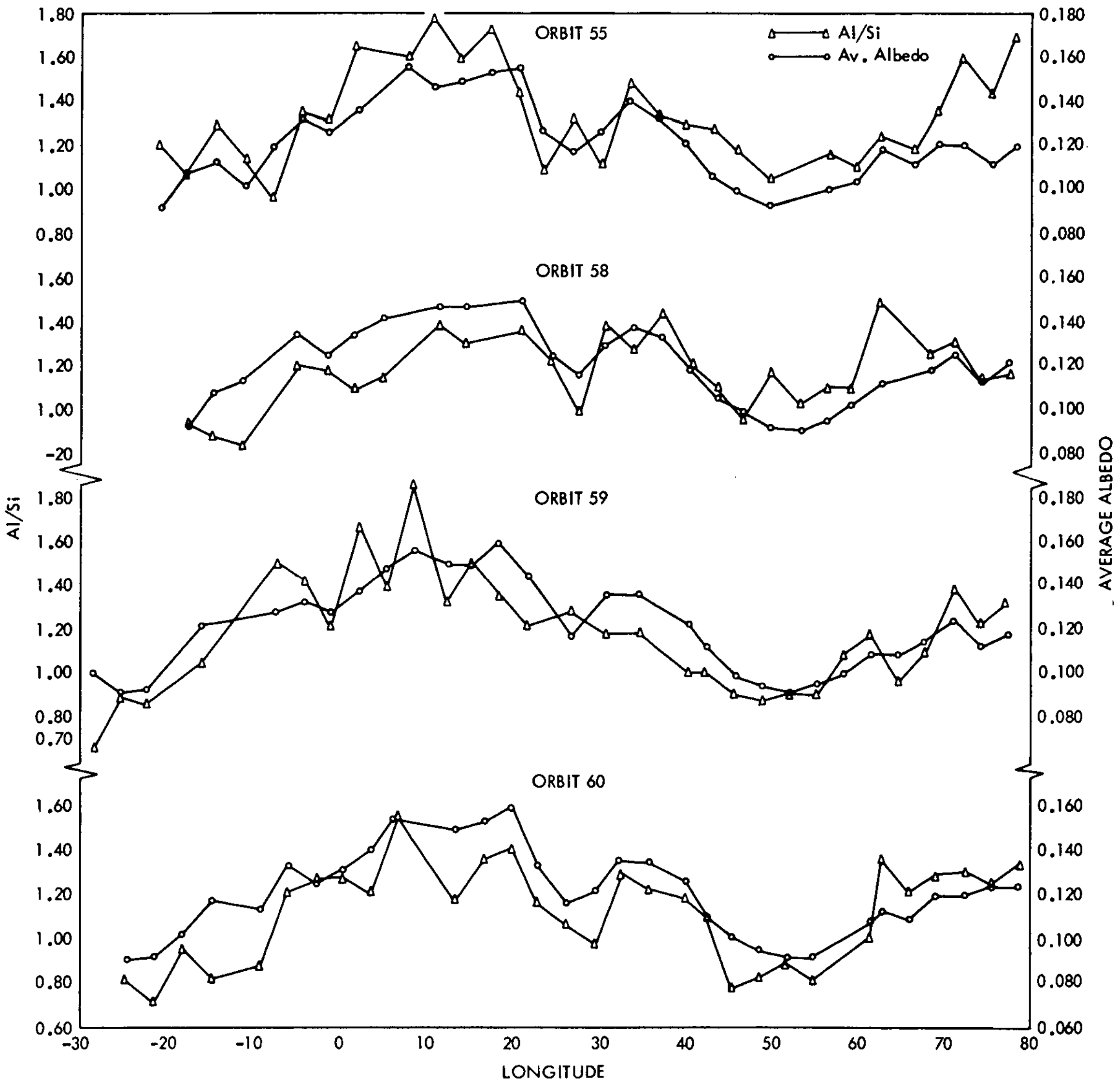


Figure 13. A Comparison of Al/Si Intensity Ratios vs. Optical Albedo Values for Various Apollo 16 Orbits

occasional increase in Al/Si although the albedo increases. This may record the existence of an old "weathered" ray consisting of aluminum rich highland derived ray material which has lost its high reflectivity.

With regard to the geologic interpretations, the Apollo 16 results generally support the conclusions reached after the Apollo 15 mission. These interpretations concern the areal extent of the inferred crustal composition and the nature and origin of the highland crust.

One of the most important aspects of the geochemical measurements is that they give a good indication of how representative the returned samples are of the lunar surface in general. The excellent agreement between the Al_2O_3 content of the returned Apollo 16 soil samples and that inferred from the X-ray measurements demonstrates that the orbital measurements are a reliable guide to at least this aspect of the moons surface chemistry. As we have shown above, the X-ray results also show that the optical albedo is a reasonable guide to the highland crustal composition.

The Apollo 16 results confirm our initial conclusions drawn from the Apollo 15 data, that the dominant rock type of the lunar highlands appear to be a plagioclase-rich pyroxene-bearing rock, compositionally equivalent to anorthositic gabbro or feldspathic basalt.

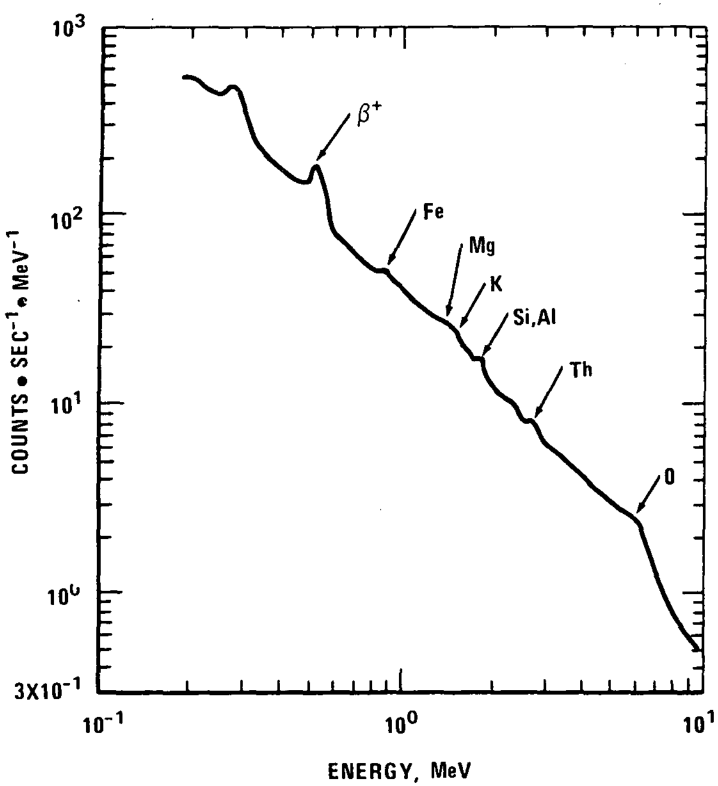
Finally the X-ray results argue against the theory that the maria are essentially filled with dust eroded from the highlands. If this were so the X-ray analysis which is essentially surficial in character would not be able to recognize the distinct contrasts in composition actually observed.

GAMMA-RAY RESULTS

Like the X-ray fluorescence experiment described above, the gamma-ray experiment performed very well on both missions. The Apollo 16 gamma-ray experiment was improved over the Apollo 15 experiment in a number of ways: The energy resolution of the spectrometer was improved from about 8.5% to 7.5% leading to better line resolution and precision; there was reduced gain drift, an increase in the amount of prime data and finally a much more rapid reduction of data.

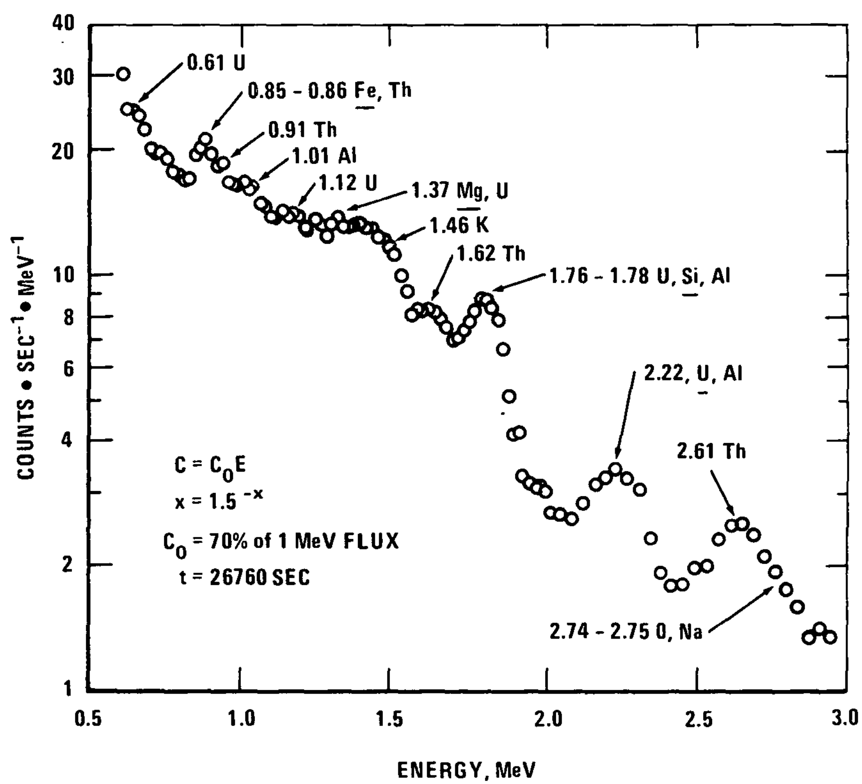
The spectrometers flown were essentially isotropic in look angle. The field of view was defined by the orbit which for both missions was nearly circular with a mean altitude of 110 km. Thus about one half of the lunar photons reaching the detector originated inside a circle of about 120 km from the subspacecraft point. Telemetry did not limit the field of view because the data was transmitted or recorded on an event by event basis.

A typical gamma-ray spectrum taken from Apollo 15 for seven hours of operation over the trajectory is shown in Fig. 14a. As was expected, the flux decreases rapidly with increasing energy and the continuum dominates over the line structure. It is possible to identify some characteristic line features attributable to both natural radioactivity and induced emission. The natural



BEFORE CONTINUUM SUBTRACTION

Figure 14 (a). A typical gamma-ray spectrum talen from Apollo 15. The spectrum is dominated by continuum.



AFTER CONTINUUM SUBTRACTION

Figure 14 (b). The observed spectrum with the continuum subtrated. The characteristic lines are now much more evident.

species are K, Th and U while the prompt gamma lines are Fe, Mg, Si and O. These lines stand out much more clearly when an estimated continuum contribution is subtracted leaving a net pulse height spectrum as shown in Fig. 14b.

Variations in lunar surface composition have been observed by accumulating the events in various energy intervals for increments of lunar surface area. A very useful energy interval is the range of 0.55-2.75 MeV because it contains the major lines due to the decay of K, U and Th as well as their daughter products. This region also includes a large proportion of the Compton scattering and pair production interactions which deposit only a portion of their energy in the detector. The observed longitudinal distribution of natural radioactivity during the Apollo 15 experiment for the nearside and farside faces of the moon has been examined. The natural radioactivity is concentrated in the Mare Imbrium-Oceanus Procellarum region. Within this region two highs are observed, one around Aristarchus and the other in the southeastern region of Mare Imbrium. The level of radioactivity falls off rapidly as one crosses into the highlands area west of Oceanus Procellarum. The highlands everywhere else are almost uniformly at the low concentration end of the scale. The one notable exception is the farside crater Van de Graaf, where interestingly enough in addition to the pronounced increase in radioactivity the sub-satellite has reported a large magnetic anomaly and the flight altimeter a major depression (13) (14).

Some preliminary results from the Apollo 16 flight are shown in Fig. 15. This is again a longitudinal track of the natural radioactivity as observed for an

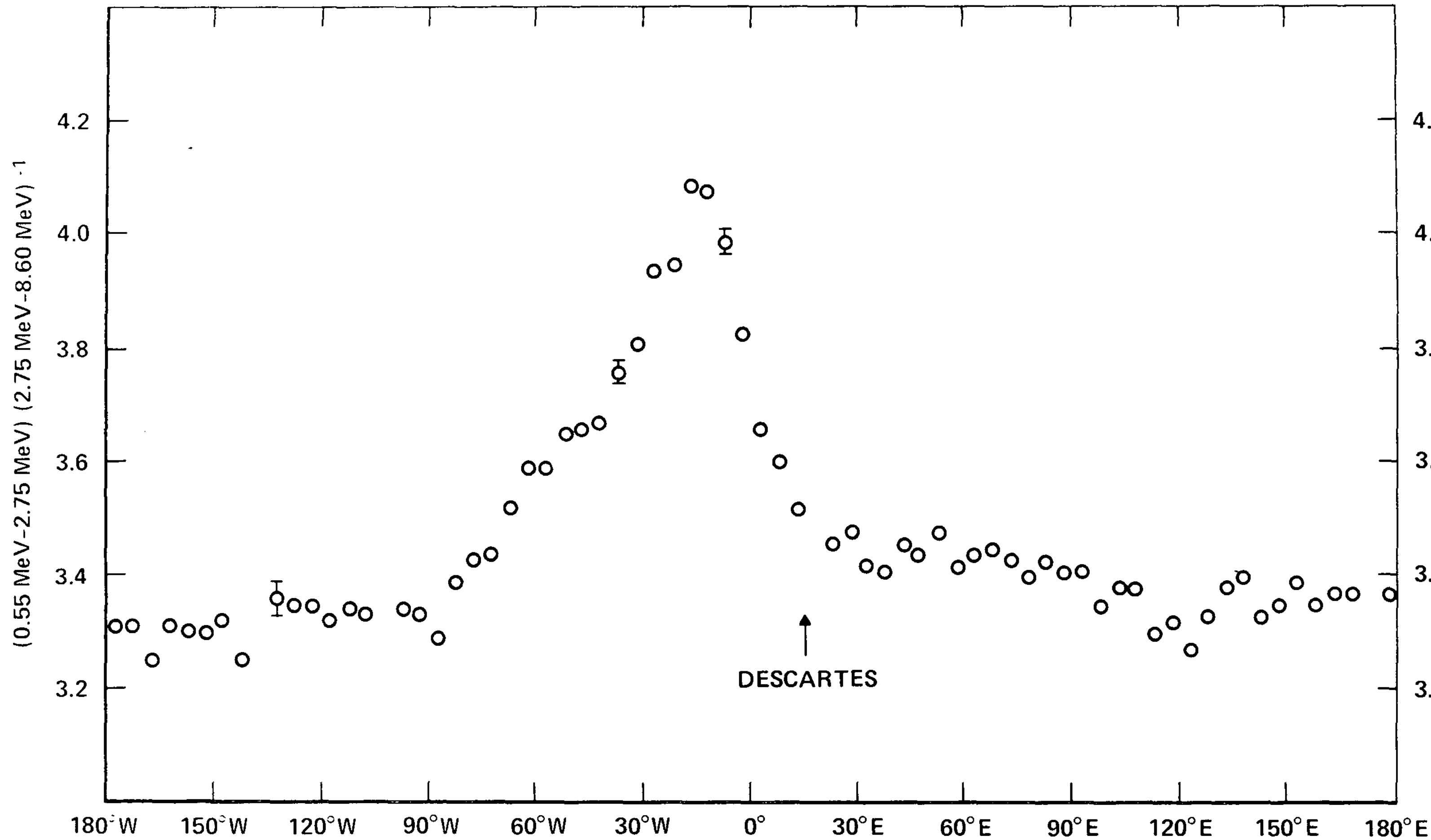


Figure 15. Apollo 16 Longitudinal Regional Accumulation for $(0.55 \leqslant E \leqslant 2.75\ \text{MeV})/(2.75 \leqslant E \leqslant 8.60\ \text{MeV})$

accumulation time of about 25 hours. The plot gives the ratio of the energy interval (0.55-2.75 MeV)/(2.75-8.60 MeV). This represents a normalization of the energy interval containing the lines from K, Th and U to the interval from which they are absent in order to correct for the effect of the topography. As in Apollo 15 the natural radioactivity is again concentrated in the western maria. The maximum is found south of Fra Mauro and is at least as intense as the maxima observed during the Apollo 15. Unlike Apollo 15 no increase is seen near 180 deg. where the Apollo 16 flew far north of the Apollo 15 track.

RESULTS OF THE ALPHA PARTICLE EXPERIMENT

The data taken during the Apollo 15 and 16 flight show that the observed alpha activity was very small; of the order of 10^{-3} counts/cm^2-sec. Three distinct types of signals were sought: alpha particles having energies consistent with the decay of ^{222}Rn and the daughter products, alpha particles from ^{220}Rn and the daughter products and finally alphas from ^{210}Po. The first two are associated with current activity and the last with events having occurred days to years previously (the presence of ^{210}Po is determined by the decay of the ^{210}Pb with its 21 year half life).

In searching for evidence of the ^{222}Rn two methods were used in processing the data. The first method involved a comparison of the counts obtained in the appropriate energy channels with the detectors looking at the lunar surface and then away. The second method involved examining the total energy spectrum and looking for an increase in those energy channels where the alphas from the ^{222}Rn were expected to occur.

An additional step in the analysis was to see if enhanced signals could be attributed to any localized area. This was done by producing a crude map of alpha activity over the ground tracks, dividing the data into bins approximately 5 deg. in longitude and variable latitudes (less than 12 deg.). Two features were obvious from the Apollo 15 data. There was a general increase in count rate over Oceanus Procellarum and Mare Imbrium. However, the increase was small enough so that further study is required. A second feature for which the data is less ambiguous is shown in Fig. 16. This second feature occurs between 45 deg. and 50 deg. W and only where the crater Aristarchus is within the instruments field of view. Fig. 16 shows the count rate for decays from ^{222}Rn and daughter products (excluding ^{210}Po). The dashed line is the approximate ground track during the period of data collection (revs. 33-46). The count rate over Aristarchus exceeds the mean count rate for the whole moon by 4.3 standard deviations.

The results from Apollo 16 are still preliminary and obtained from some of the "quick look data" obtained while the mission was in progress. At this writing there is still no evidence of "hot spots" from ^{220}Rn or ^{222}Rn. There is however strong evidence for the existence of decays from ^{210}Po, indicated by a statistically significant higher count rate centered over the Mare Fecunditatis.

1. PLATO 2. SINUS IRIDUM 3. MARE IMBRIUM 4. SINUS RORIS 5. SCHRÖTER'S VALLEY 6. ARISTARCHUS 7. MARIUS HILLS 8. MARIUS 9. COPERNICUS 10. KEPLER 11. REINER GAMMA 12. HEVELIUS 13. KUNOWSKY 14. LANSBERG 15. FLAMSTEED 16. MARE COGNITUM 17. GASSENDI 18. MARE HUMORUM 19. TYCHO

Figure 16. The variation of ^{222}Rn superimposed upon a photograph of the moon. The dashed line represents the average ground track during Apollo 15 orbits 34-46. It is also the base-line for the data.

The conclusions drawn from the Alpha experiment on Apollo 15 and 16 is that there are areas on the moon with locally high emanations. The most conspicuous feature is in the region which includes the crater Aristarchus. The enhanced activity may be an indication of internal activity at the site. The existence of regions showing some ^{210}Po activity is perhaps an instance of some previous, transient phenomenon involving the release of ^{222}Rn from some area of the moon.

GALACTIC X-RAY OBSERVATIONS

During the trans-earth coast period during both missions the X-ray fluorescence spectrometers were used to observe the temporal behavior of two pulsating X-ray stars within our galaxy; Sco X-1 and Cyg X-1. The primary objective was to measure the variations in X-ray luminosity of both these objects and by coordinating with ground based observations attempt a correlation with optical and radio activity. A secondary objective was to study the cis-lunar space environment as a site for pointed X-ray astronomy; specifically, the determination of backgrounds in the X-ray detectors from trapped electrons or protons as compared to the near earth and moon environments.

Much has been learned from recent satellite observations about the nature of pulsating X-ray sources in the period between Apollo 15 and 16. It is clear that these objects fall into several classes. One class of which Cen X-3 is an example is characterized by a highly regular period of several seconds plus additional periods of several days (15). The observations of this class seem to require a binary system involving a low mass star (16), possibly a white dwarf. This class of object if comparatively well understood, at least observationally, and from their characteristic periods are not in a time regime suitable for study by the use of the X-ray Fluorescence experiment.

A particularly intriguiging X-ray source is Cyg X-1. This has been identified with a massive BO star (17) whose spectrum indicates a binary star system, an identification that has strengthened the case of those arguing that a "black hole" is involved in the X-ray production. Their models propose that X-rays originate from the accretion of matter upon a dark binary companion of the massive star. The fast time variability in X-ray luminosity of Cyg X-1 (significant changes in less than one second), (17), requires that the dark companion be compact, with a radius no larger than that of a white dwarf. From present theories such a binary companion of the BO star would be stable only as a "black hole". Thus from these considerations Cyg X-1 is perhaps the most provocative of all galactic stars. As a consequence about half of the available Apollo 16 pointing time was devoted to its observation. The remainder of the time during trans-earth coast was used for observing Sco X-1, the most intense of all observed galactic X-ray sources. Further Sco X-1 is also identified with a visible and radio star.

Specifically the hope was to determine if the behavior of Cyg X-1 and Sco X-1 was similar on a time scale larger than several seconds, and if they were examples of related objects under somewhat different physical conditions.

Arrangements were made with a network of ground based observatories to cover Sco X-1 and Cyg X-1 at various times during the Apollo 16 mission. The cooperating optical observatories included: The Crimean Astrophysical Observatory (USSR), Leyden Observatory (South Africa), Wise Observatory (Israel), McDonald Observatory (USA), and the Yerkes Observatory (USA). The radio facilities were Westerbork Observatory (Netherlands), Algonquin Observatory (Canada) and the National Radio Astronomy Observatory (USA).

OPERATION OF THE EXPERIMENT

The proper performance of the astronomy measurements required the pointing of the X-ray spectrometer at the selected celestial point for the entire interval of one to two hours. Because of the rather large field of view, the instrument was intentionally pointed 7 deg. away from Sco X-1 and Cyg X-1 in order to minimize contributions from other celestial sources. About 10 hours of X-ray data was obtained, divided between Cyg X-1 and Sco X-1. Because of some mission difficulties the trans-earth coast occurred one day early and created some difficulties in coordinating with the ground observation program. As a consequence there was reduced optical and radio coverage.

RESULTS

Examination of the data from Sco X-1 and the spacecraft navigational parameters disclosed that there were changes in count rate. Part of the variation came from the spacecraft motion, but a significant change originated in Sco X-1.

In general Sco X-1 was active during the first sighting. Allowing for the spacecraft motion, significant changes (10-30%) in intensity were identified in a few minutes. Although there was no simultaneous optical and radio data, subsequent reports received from the McDonald and Algonquin Observatories indicated that Sco X-1 was active in the optical and radio regions. Flare activity was detected at the ground observatories.

There were also two observations of Cyg X-1 during the Apollo 16 mission. While two large increases in count rate were observed, neither one appeared to be intrinsic to Cyg X-1. The indications were rather of a sudden increase in particle background. However there was a marked change in X-ray intensity between two subsequent sightings. Cyg X-1 appeared twice as intense in the second sighting.

The conclusions that have been drawn is that Sco X-1 is characterized by both quiet periods as well as active ones. During the active periods the intensity can change by as much as 10-30 percent in a few minutes. Further these active periods can last for at least a day. When Sco X-1 shows changes in X-ray intensity there are concurrent but not necessarily simultaneous changes in its optical and radio intensity.

Cyg X-1 can double in intensity within a day or so. These changes were observed to occur in the energy ranges of 1-3 keV, $>$ 3 keV and $>$ 7 keV. Sco X-1 showed a greater variability than Cyg X-1 on a time scale of a few minutes, at least during the Apollo 16 flight.

Finally it was observed that transient particle effects in cis-lunar space could occur and last for several minutes. These events, for detectors with a broad field of view can be mistaken for flares in X-ray stars.

SUMMARY

The Apollo 15 and 16 missions have been among the most successful of the Apollo missions in terms of scientific yield. The orbital experiments worked particularly well, furnishing information about the moon as well as data about the galaxy. The X-ray and gamma-ray experiments enabled us to map a relatively large part of the moon geochemically. These experiments clearly demonstrated that the moon's crust is chemically differentiated and the highlands feldspathic in character. Historically we were able to learn something about the moon's hidden face. The gamma-ray measurements showed an as yet unexplained assymetry in the distribution of the radioactive elements K, Th and U. The alpha experiment showed an interesting increase in alpha emission in the region of Aristarchus which may perhaps indicate a still active region on the moon. Finally the galactic measurements provide some information on the behavior of Sco X-1 and Cyg X-1 on a longer time scale than had previously been observed.

REFERENCES

1. Vinogradov, A. P., Surkov, Y. A., and Chernov, G. M., Doklody A. N. SSSR, Tom 170, No. 3, 561, Moscow, 1966.
2. Turkevich, A. L. et. al., Jet Propulsion Laboratory Tech. Rept. 32-1265, Surveyor Project Final Report, p. 303, 1968.
3. Lowman, P. D. Jr., Journal of Geology, V. 80, No. 2, p. 125, March 1972.
4. Mandel'Shtam, S. L. et. al., Kosmicheskiye Issledovaniya, Tom 6, Vupusk 1, 119, Izdatel'stvo "Nauka", 1968.
5. Kraner, H. W. et. al., Science 152, 1235, 1966.
6. Ready, R. and Arnold J., private communication, Univ. of Calif., San Diego, Calif., 1970.
7. Solar-Geophysical Data, U.S. Dept. of Commerce, 1972.
8. Tucker, W. H., and Koren, M., Astrophys. Jour., 168, 283, 1971.
9. Gorenstein, P. et. al., Advan. X-ray Anal., 13, 330, 1970.
10. Eller, E., Personal Communication, Goddard Space Flight Center, 1971.
11. Adler, I. et. al., Apollo 15 Preliminary Science Report, NASA SP-289, p. 17-1, 1971.

12. Whitaker, E. A., The Nature of the Lunar Surface, The Surface of the Moon, editors Hess, W. N., Menzel, D. H. and O'Keefe, J. A., p. 79, The Johns Hopkins Press, 1965.

13. Coleman, P. J. Jr. et. al., Proceedings of 3rd Lunar Science Conference, Lunar Science Institute, Houston 1972 (to be published).

14. Koula, W. M. et. al., Proceedings of 3rd Lunar Science Conference, Lunar Science Institute, Houston 1972 (to be published).

15. Schreier, E. et. al., Ap. J. (Letters) 172, L79, 1972.

16. Wilson, T. E., Ap. J. (Letters) 174, L27, 1972.

17. Webster, Land Murdin, P., Nature 235, 37, 1972.