INVESTIGATION OF SOLAR SYSTEM OBJECTS BY NUCLEAR PHYSICS METHODS

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Abstract

Exploration of the planets must be largely carried out by remote observational techniques. The determination of the elemental composition of a planet allows important constraints to be placed on its origin and evolution. It can be addressed by measuring gamma ray spectra and neutrons from orbiting spacecraft. Gamma ray lines used for most elemental studies are made by inelastic-scattering reactions of neutrons with a few MeV of energy or by capture reactions of neutrons near thermal energies. The neutron spatial and energy distributions were calculated using the LAHET Code System (LCS) for the simulation of cosmic ray interactions with a target body. Having calculated the particle fluxes, the production rate of concrete gamma ray is obtained by integration over energy of the product of these fluxes and corresponding excitation function for the production of this gamma ray from particular target element. Measured or evaluated cross sections are used for inelastic or spallation reactions. After the depth-dependent production rates for gamma rays are calculated, we calculate the transport of gamma rays from their source to the detector. The planetary surface neutron flux was calculated as a function of variations in the hydrogen concentration and the macroscopic thermal-neutron absorption cross section. These variables cover a wide range of possible planetary compositions. The effect of thin atmospheres, such as that of Mars, was also studied. Obtained results of simulations were compared with real data from various space missions.

1. Introduction

Achieving an understanding of the initial conditions of the solar nebula, the processes for the formation and subsequent evolution of planetary bodies, and the processes currently active in the solar system are among the major scientific goals of any planetary mission. The determination of the elemental composition of a planet allows important constraints to be placed on its origin and evolution. Unlike the Earth, where it is practical to collect and analyze samples in abundance, the exploration of planets must be carried out largely by remote observational techniques. At the present time a variety of passive and active remote-sensing techniques are available, and they can provide much of the needed information. For conducting planetary reconnaissance and global surveys from orbit, the most commonly applied technique is passive remote sensing, in which the source of radiation is supplied from outside. The radiation field in the vicinity of the planet induces processes leading to chemically characteristic products. Orbital measurements can be carried out only if the planet's atmosphere and magnetic field do not significantly interfere with the incident cosmic rays and the detectable products of their interactions. X-ray fluorescence from solar X-rays can provide the relative abundances of the elements from atomic numbers of about 6 to about

20 *[Haines et al., 1976]*. To a limited extent, alpha-particle and mass spectrometers give data on the surface composition *[Hodges and Hoffman, 1973]*. Neutron albedo can be used to determine the presence of hydrogen in a planet's surface *[Lingefelter et al., 1961]*. Visible imaging, with the possibility to obtain images in narrow spectral bands from the ultraviolet through far-infrared, enables identification of molecular species, ices, organics, and minerals via electronic and molecular vibrational transitions. Gamma-ray emissions due to cosmic-ray bombardment of the surface, as well as from the decay of naturally occurring radioisotopes, allows determination of many elemental abundances *[Reedy et al., 1973]*. An up-to-date review of different remote-sensing techniques can be found in *Pieters and Englert, [1993]*. Numerical simulations of γ-ray production in planetary surfaces will be described in detail in this paper.

The γ-rays escaping from planetary bodies such as the Moon, Mars, asteroids, and comets can be detected by remote-sensing systems carried aboard spacecraft. These γ-rays can be used for the construction of global geochemical maps of the top few tens of centimeters of the surface *[Reedy et al., 1973]*. Planetary gamma-ray spectrometry was proposed around 1960 *[Lingenfelter et al., 1961; Arnold et al., 1962; Van Dilla et al., 1962]*, but planetary missions with such instruments have been very rare. NaI(Tl) scintillation gamma-ray spectrometers were flown on the Apollo 15 and 16 missions in 1971 and 1972. They produced valuable information about the elemental composition of about 20\% of the Moon's surface *[Bielefeld et al., 1976; Etchegaray-Ramirez et al., 1983]*. The Soviet Mars 5 and Phobos missions included CsI(Tl) gamma-ray spectrometers, which obtained little quantitative data on elemental abundances *[Surkov et al., 1989; Trombka et al., 1992]*. A high-resolution γ-ray spectrometer was on Mars Observer *[Boynton et al., 1992]*, and the martian γ-ray fluxes reported here were calculated for getting elemental abundances from measured martian γ-ray line fluxes. Although Mars Observer was lost, γ-ray experiments were flown on Lunar Prospector, NEAR – Shoemaker that investigated asteroid 333 Eros, Mars Odyssey, MESSENGER investigating Mercury, Kaguya and for other orbital and surface missions.

For the interpretation of measured γ-ray fluxes in terms of the chemical composition of a planet's surface, a precise and accurate simulation of the production and transport phenomena is required. Such simulations were carried out by various authors for the lunar surface, and several works were also devoted to Mars. The lunar neutron spectrum, including the calculation of capture rates from trace elements, was studied in detail by *Lingenfelter et al. [1972]*. *Armstrong [1972]* used Monte Carlo methods to calculate he lunar neutron albedo. Using particle fluxes proposed by *Reedy and Arnold [1972]*, *Reedy et al. [1973]* and *Reedy [1978]* calculated the lunar gamma-ray leakage for a large number of gamma-ray lines. Basic studies of gamma-ray emission spectra from the martian surface were performed by *Metzger and Arnold} [1970]*. Various aspects of martian gamma-ray spectra were investigated by *Lapides [1981]*. *Evans and Squyres [1987]* studied the effect on γ-ray fluxes of composition and of various structures such as polar caps.

The majority of the above-mentioned models used various approximations with a very limited set of input parameters or were performed in simplified one-dimensional geometries. The disadvantage of Monte Carlo approaches lies in the incomplete coupling of the high- and low-energy parts of calculations. In some cases, the input distributions for the production of gamma rays from low-energy neutrons were taken from a separate calculation made independently from the high-energy model. These problems were overcome by *Dagge et al. [1991]*, who used the HERMES code system for the calculation of a few γ-ray line fluxes from lunar and martian surfaces.

Studies of the influence of various parameters on γ-ray fluxes from the martian surface require detailed numerical simulations that can only be achieved with physical models. To simulate numerically all processes relevant in particle production and transport, the physical model that we applied to the investigation of γ-ray line fluxes from the martian soil and atmosphere uses only basic physical quantities and principles, without including any free parameters. Our model has previously been tested for cosmogenic nuclide production in meteorites *[Reedy et al., 1993; Masarik and Reedy, 1994a]* and in the lunar surface *[Reedy and Masarik, 1994]*. It has also been tested in the reproduction of experimental data from laboratory simulations of martian neutron distributions *[Drake et al., 1994]*. As our model enables us to follow the history of individual cosmic-ray particles in the martian atmosphere and soil, we are able to determine the main sources of differences in the behaviour of cascade particles in various environments. This detail has made it possible to study the effects of atmospheric thickness, water content in martian soil, and macroscopic thermal-neutron absorption cross sections on the production and transport of secondary particles, which in turn determine the eventual γ-ray line fluxes above the martian surface. Preliminary results for the line fluxes were reported in *Masarik and Reedy [1994b]*. A complete discussion was published in *Masarik and Reedy [1996]*.

2. SOURCE OF GAMMA RAYS

Gamma-ray emission from planetary surfaces results from several processes *[Reedy et al., 1973; Reedy 1978}]*. The gamma rays of interest for geochemical mapping are those that arise on nuclear transitions between well-defined states and hence have unique, sharply defined energies. They are scattered or absorbed in the surface layer and in the atmosphere with a probability dependent on energy. Thus the gamma rays reaching an orbiting spectrometer originate mainly in the upper 50 cm or less of the surface.

There are two principal ways that excited levels of nuclei are formed in planetary surfaces, both of which are investigated below: decay of radioactive isotopes and excitation by cosmic-ray particles. The naturally radioactive elements Th, K, and U emit gamma-ray lines either directly or in the course of their decay chains. These lines are emitted at a rate strictly proportional to the elemental concentration. Fluxes of these gamma-ray lines are relatively easy to calculate because they usually require only basic nuclear parameters such as isotopic abundances, half-lives, γ-ray yields per decay, and γ-ray transport properties.

The second source of γ-ray lines is the interaction of cosmic rays with planetary material. This source is very complicated; as one needs to start with the high-energy (GeV) particles present in the galactic cosmic rays (GCR) and follow the subsequent and secondary particles until a γ-ray is produced. There is a variety of reactions, but most lines originate from two processes, both involving bombardment by secondary neutrons. The first is neutron inelastic scattering, which raises the target nucleus to excited states with a few MeV of energy. The second is thermal or epithermal neutron capture, the so-called (n,γ) process. In this case the excited nucleus typically has energy of a few MeV, which is dissipated in a cascade of gamma rays, a few of which usually appear with high yields *[Reedy et al., 1973; Bielefeld et al., 1976]*. The huge energy range of the projectile particles that participate in reactions leading to γ-ray production requires a very complex nuclear model for the simulation of relevant processes. Besides neutrons, protons (primary and secondary) are the most frequently produced particles in these reactions, and their possible contribution to γ-ray production by inelastic scattering reactions must be considered in any realistic calculation. In addition, primary cosmic rays produce a small amount of gamma radiation from spallation reactions.

As can be seen from the preceding discussion, any process that can affect the neutron flux, either at thermal and epithermal energies or at energies above 1 MeV, can alter the resulting γ-ray flux. As shown later, neutrons are generally produced with energies of ~0.1--10 MeV and occasionally higher. A neutron usually must scatter many times to reach epithermal and thermal energies, during which time it can travel through the object of interest or escape from it. This transport of neutrons to low energies is an additional complication in studying γ rays produced by neutron capture. Though neutron inelastic-scattering reactions are less sensitive to particle production and transport processes, the understanding of the equilibrium neutron flux in the planetary surface and the parameters that affect it are nevertheless the keys to understanding planetary γ-ray fluxes.

3. LCS MODEL FOR CALCULATION OF γ-RAY FLUXES}

In our model, the fluxes of particles inducing nuclear reactions in which γ-rays are produced were calculated using the Los Alamos LAHET Code System *[Prael and Lichtenstein, 1989]*, which is a general-purpose Monte Carlo computer code system that treats the relevant physical processes of particle production and transport. Neutrons with energies below 20 MeV are transported by Monte Carlo N-particle (MCNP) code *[Briesmeister. 1993]*. This code transports neutrons down to thermal energies. LCS, its tests, the basics of its physical model, and its adaptation to planetary applications are described in *Masarik and Reedy, [1994}]*, and therefore only the information most important for the γ-ray flux calculations is given here.

LCS is used to simulate the processes related to the production of γ-rays emerging from inelastic scattering or neutron capture. The model for the calculation of γ-ray line fluxes from the decay of naturally radioactive elements is given below. The GCR proton spectrum was used as input for the LAHET code. While LCS can calculate γ-ray line fluxes as one of its outputs, we used this option only for the production of γ-rays in neutron-capture reactions, where the MCNP code is coupled to state-of-the-art neutron capture cross sections. In all other cases we used LCS only to calculate the fluxes of particles that lead to γ-ray production. Assuming isotropic irradiation of the sphere with radius *R* by GCR particles, the photon production rate of line *j* at a depth *D* is

$$P_j(R,D) = \sum_i N_i \sum_k \int_0^{\infty} \sigma_{ijk}(E_k) J_k(E_k, R, D) dE_k \tag{1}$$

where N_i is the number of atoms for target element *i* per kg material in the sample, σ_{ijk} is the cross section for the production of γ-ray line *j* from target element *i* by particles of type *k* with energy E_k, and $J_k(E_k,R,D)$ is the total flux of particles of type *k* with energy $\mathrm{E_k}$ at location *D* inside the irradiated body. As stated earlier, the particle fluxes $J_k(E_k,R,D)$ are calculated using LCS, and the cross sections σ_{ijk} were ones evaluated by us and tested in earlier calculations *[e.g., Reedy et al., 1973; Reedy, 1978]*. The π mesons generated in large numbers by LAHET are also a strong source of γ rays, which contribute to the background in the γ-ray line spectrum. Neutral pions are forced to decay at the site where they are created, which is justified by their very short half-life.

In going from the source to the detector, a gamma ray can vanish entirely (e.g., photoeffect) or its multiple interactions within the planetary body (e.g., Compton scattering) can produce a continuous spectrum in the energy range of interest. The total gamma ray-spectrum is thus the sum of the line spectrum, the photons from π^0-decay, and this continuous spectrum. In almost all applications of γ-ray spectroscopy, only gamma rays that arrive at the detector without changing energy are used for mapping elements.

4. **CALCULATIONAL PROCEDURE**

The simulation of particle production and transport processes begins with a choice of the primary particle type and its energy. The martian surface was modelled as a sphere irradiated by a homogenous, isotropic particle flux. γ-gamma rays resulting from nuclear reactions induced by solar-cosmic-ray (SCR) particles are much less important for Mars than for Moon for two reasons. First, because the long-term average fluxes of SCR particles at Mars is only 19-28 % of those at the Moon. Second, SCR particles have low energies and therefore induce nuclear reactions only in the outermost few g/cm^2 of the martian atmosphere. Because we were predominantly interested in the production of γ-ray lines from the martian soil, we considered only GCR as input particles. Galactic cosmic rays consist of 87 % protons, 12 % alpha particles, and ~1 % heavier nuclei with atomic numbers from 3 to ~90. If energies are expressed as per-nucleon values, the spectral distribution of the heavier particles is quite similar to that for protons. The differential GCR proton flux used in our simulations is taken from *Castagnoli and Lal [1980]* with modulation parameter corresponding long-term average flux.

In our calculations, Mars was modeled as a sphere with the real martian radius (3390 km). The assumed chemical composition of martian soil is given in *Boynton et al., [1992]*. To study the influence of water content in soil on γ-ray production, we carried out calculations for 0, 0.1, 0.3, 1, 3, 10, 30, and 90\% water content. For each water content the chemical composition was normalized in such a way that the sum of the weight fractions of all elements present in a particular chemical composition was 1.0. A homogenous distribution of all elements in the martian soil and atmosphere was assumed in all cases.

As the particle production and equilibrium spectra are strongly depth-dependent, the martian sphere was divided into concentric shells of varying thickness, with many layers near the surface and fewer layers at greater depths. The thickness of a shell resulted from the compromise between two opposite requirements: the minimization of statistical errors in the calculations, which are approximately inversely proportional to the shell thickness, and the investigation of the depth dependence of the particle fluxes, which can be more precisely described by splitting the investigated body into finer shells. The importance of the second requirement is underscored by the fact that in the energy range of interest about 90\% of all γ-rays reaching the surface come from depths less than one mean thickness ($1/\mu$), where μ is mass attenuation coefficient.

The influence of the martian atmosphere on production and transport phenomena was also investigated. In all the calculations reported here, the density of the martian atmosphere was approximated as an exponential function with a height scaling factor of 10.8 km. The normalization constant of this function, ρ, was selected so that the integral thickness of the atmosphere stepped between 5 and 25 g/cm^2. In all cases, the atmosphere was divided into 20 concentric shells of equal thickness. The upper boundary of the atmosphere was 200 km above the martian surface. The influence of the atmosphere on the development of particle cascades, the attenuation of γ-ray lines, and the production of γ-rays in the martian atmosphere and their interference with those produced in martian soil were also investigated.

The source term, that is, the rate at which a gamma ray is produced is for γ-rays emerging from neutron capture and neutron inelastic scattering reactions calculated according to Eq. (1). Once the source term is known, the transport of the gamma rays from their point of creation to the detector must be considered. In most cases, the gamma-ray detector will be above the planet's surface, such as on an orbiting satellite. In the calculation of fluxes at the detector, the geometry and effects related to the attenuation in passing through the martian atmosphere had to be included.

5. COMPARISON OF EXPECTED FLUXES WITH EXPERIMENTAL DATA

As mentioned in the introduction, numerous results can be obtained with our model for the simulation of cosmogenic nuclide production in objects of various sizes and chemical compositions. In most cases the agreement between experimental data and calculations is good. We calculated several γ-ray line fluxes for a lunar composition *[Reedy, 1978]*, using the primary cosmic-ray nucleon flux of 4.56 nucleons/cm^2/s. Ratios between the fluxes calculated using the model of Reedy and Arnold and those calculated using LCS show that the fluxes calculated by LCS are higher for all the presented lines. Since the photon production and cross-section data used in both calculations are the same (they are those used in *Reedy [1978]*), differences between the results can only be attributed to differences between the neutron fluxes obtained by LCS and those assumed by the model of Reedy and Arnold. Comparison of neutron fluxes calculated by these two models reveals a difference in their spectral shape as well as in their depth dependence. As all calculated depth profiles presented above are in a good agreement with the measured data in both shape and absolute value, the calculated particle fluxes seem to be realistic and appropriate for the prediction of gamma-ray fluxes. Results of simulations were used for deconvolution of data obtained in a few missions.

Example of the successful mission can be NEAR that was flown to asteroid 433 Eros. Data obtained by this mission were used for the determination of the chemical type composition of 433 Eros. Gamma ray spectra obtained in the 35 km orbit are given in Fig. 1.

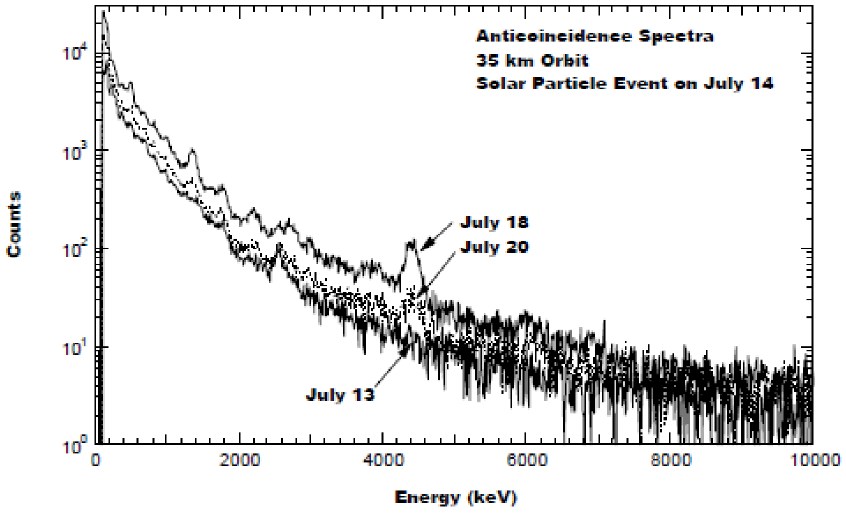
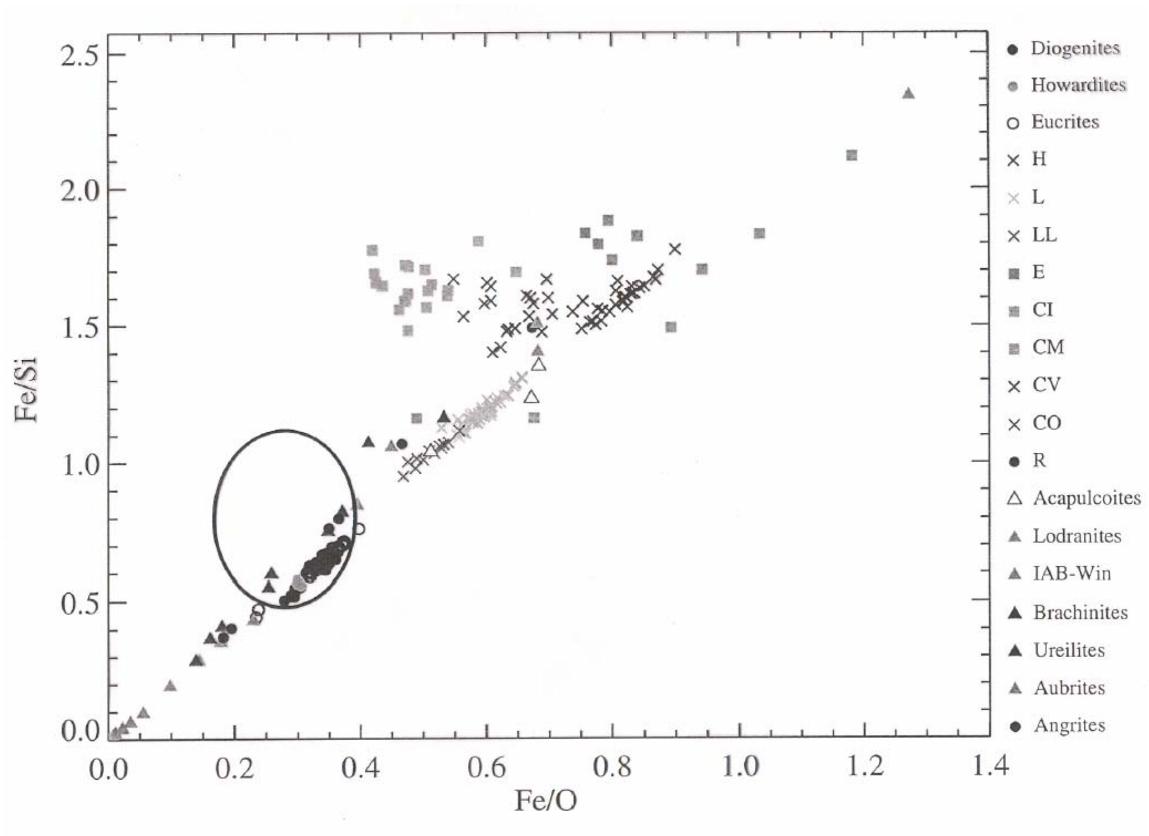


Figure 1. Three spectra taken by NEAR gamma ray detector during July 2009 in the 35 km orbit [Evans et al., 2001].

Obtained spectra were used for the determination of unique elements concentrations. Comparing the ratios Fe/Si and Fe/O with values typical for particular meteorite types, it seems that composition of 433 Eros is similar to L and LL chondrites.



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