PLANETARY GAMMA-RAY SPECTROSCOPY OF A COMET SURFACE;
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Planetary gamma-ray spectroscopy is a very capable tool to explore the surface of a comet nucleus. The gamma rays emitted from the surface carry qualitative and quantitative information on many elements present in the surface. We studied the gamma-ray emission of comets with different chemical compositions and surface geometries. Monte Carlo calculations were performed to simulate the cosmic-ray interactions with the comet surface and the subsequent emission of gamma rays. Our calculations show that the evaluation of gamma-ray spectra provide fairly accurate information on concentrations of all major elements. The planned gamma-ray measurements that will be carried out during the ESA comet mission Rosetta, will contribute to the detailed investigation of the surface of a comet and in conclusion to its history and origin.

Most theories about comets assume that they are pristine planetesimals that formed in the postulated Oort cloud or the Kuiper belt during an early period of the solar system. Recent observations of the Hubble Space telescope seem to confirm the existence of objects in the Kuiper belt. This implies that comets are the least differentiated bodies of the solar system, they accreted in low-gravity fields, and existed for most of their lifetime in an extremely cold environment. One important aspect of the origin of a comet will be its relationship to carbonaceous chondrites of type CI [1] that match in most elements the composition of the Sun except for highly volatile elements [2]. Since comets can be considered as snowy dust balls [3], it can be expected that their rock components resemble the composition of CI, while their elemental abundances of H, C, N, O are closer to the composition of the Sun than to CI.

Rosetta is a European Space Agency (ESA) mission designed to rendezvous with comet Wirtanen and perform remote sensing investigations as well as carrying two probes to land on the comet's surface and perform in situ measurements. In August 2012, the probes, named RoLand and Champollion, with the surface science packages will be released for soft landing. An advanced gamma-ray spectrometer (GRS) will be part of the payload of the probe Champollion.

The comet is permanently bombarded by energetic galactic cosmic rays (GCR) that results in nuclear interactions with surface matter and is the main source of gamma rays besides natural radioactivity. Since the production process of secondary particles is very complex, the major portion of the gamma ray emission is a continuum. The production of secondary neutrons provides typical gamma rays that result from $(n,n\gamma)$ scattering reactions and (n,γ) capture reactions of fast and thermal neutrons, respectively. These discrete-energy gamma rays in the range from 10 to 0.1 MeV are diagnostic to the composition of the surface material. Their specific energies are used for the identification of the emitting nuclei, i. e. the elements present in the surface, while their intensities reflect the concentration of the elements, i. e. qualitative and quantitative analysis of the landing site is possible [4]. These data will be used to determine the elemental composition of the rock component and the ice component, and to derive the rock to ice ratio of the surface. This local information will be brought into context with the information gained by all other instruments located on both landers and the orbiter. The compositional data will reveal the validity of the above outlined hypothesis of the origin of comet Wirtanen or may suggest an exceptional history.

Different types of gamma-ray spectrometers were used in past to remotely measure planetary gamma rays: either low-resolution scintillation detectors or high-resolution germanium detectors [5]. High energy resolution is wanted to unravel the complex gamma-ray radiation emitted by the comet surface. The gamma-ray spectrometer of the Champollion payload will be an exceptional very light-weight instrument and will contain a germanium crystal [6]. The detector must be operated at temperatures below 130 K that can well be achieved by passive cooling in the cold environment of a comet. During the long cruise phase, detector radiation damage will build up that will be removed by heating the germanium crystal to temperatures of around 100°C prior to landing [7].

To prepare the analysis of the comet surface extended simulation calculations were carried out. These calculations are based on the Los Alamos LAHET Code System (LCS) [8], which is a system of general-purpose, continuous-energy, generalized-geometry, time-dependent, off-line coupled Monte Carlo computer codes that treat the relevant physical processes of particle production and transport. This code system and its application to planetary problems is in more details discussed in [9]. An isotropic GCR flux is simulated by 4.56 protons/cm^2/s corresponding to the GCR primary particle spectrum averaged over a typical solar cycle, spread out over of a sphere with a radius of 2 km. It was assumed that the comet surface consisted of a rock and ice component. The rock component was closely matched to the composition of CI. The elemental composition of the surface was varied by changing its ice content from zero to 90 %.

The cometary nucleus was divided into concentric shells, with many shells near the surface and fewer shells at greater depths. Having calculated the neutron fluxes for each shell, the production rate $P_j(R,r)$ of gamma rays j at distance r from the center of an comet with a radius R was calculated with:

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$$P_j(R,r) = \sum_i N_i \sum_k \int_0^{\infty} \sigma_{jik}(E_k) \cdot J_k(E_k,R,r)\,dE_k$$

where N_i is the number of atoms for target element i per kg material in the irradiated body, σ_{ijk} is the cross section for the production of gamma ray j from target element i by particle of type k with energy E_k, and $J_k(E_k,R,r)$ is total (primary plus secondary) flux of particles of type k with energy E_k inside the irradiated body. Measured or evaluated cross sections were used for inelastic or spallation reactions.

For the expected gamma-ray line fluxes we did not deal with scattered gamma rays, which contribute to the gamma-ray continuum, but only with the gamma rays that undergo no interactions before they reach the surface. Therefore, having calculated production $P_j(R,r)$ of gamma ray j at each distance r from the center of the comet nucleus, we determined the flux of gamma rays at an isotropic detector on the cometary surface with:

$$F = \int_0^{2\pi} d\varphi \int_0^{\beta_{max}} P_j(R,r) \cdot \sin\beta \cdot e^{-\mu \cdot l(\beta)}\,d\beta$$

where $l(\beta) = (r^2+R^2-2 \cdot R \cdot r \cdot \cos\beta)^{1/2}$ and β is the angle between the lines connecting the point of gamma-ray creation and detector position with the center of comet nucleus, respectively, and μ is the exponential mass attenuation coefficient for that gamma ray. The integral over depths was only done to a depth below which very few gamma rays escape, in our case 4 m. The coefficient for each gamma ray was also corrected for actual ice content in the simulated chemistry.

In addition to the gamma-ray flux lines, the general gamma-ray continuum was evaluated. This can be used to calculate the required counting time of each element to achieve a preset error assuming a germanium crystal size of 45 x 50 mm. A suite of comet compositions and several layering geometries of rock and ice were evaluated. Results of one selected comet composition consisted of 50 % CI material and 50 % ice, which contained 45 % H_2O, 45 % CO_2, and 10 % HCN, is shown in Table 1. Strong characteristic gamma-ray lines were chosen for all important elements, which are ordered by increasing counting time. It can be seen that H, Fe, O, K-40, Si, Mg, C, and S can be measured with an error of 10 % within 50 hours of counting time. Since the concentrations of U and Th are very low in CI, they cannot be determined, but, considerable enrichments would be detectable. As it will be demonstrated elsewhere, the reliability of these calculations is very accurate.

El.	Energy [MeV]	Mode	Concentr. [%]	Flux [a]	Error **10%** Time [hours]	Error **30%** Time [hours]
H	2.223	C	3.46	7.438	0.20	0.02
Fe	0.847	I	9.15	0.426	3.22	0.36
O	6.129	I	59.84	1.979	3.69	0.41
K-40	1.461	N	3.03E-4	0.535	3.90	0.43
Si	1.779	I*	5.34	0.439	5.71	0.63
Mg	1.369	I	4.68	0.331	7.08	0.79
Fe	7.631	C	9.15	1.501	7.41	0.82
C	4.438	I, d	10.10	0.802	38.1	4.23
S	5.424	C	2.90	0.316	47.3	5.26
Si	3.539	C	5.34	0.187	58.4	6.49
S	2.379	C	2.90	0.129	59.7	6.63
U	0.609	N	4.12E-7	0.009	2715	302
Th	2.614	N	1.45E-6	0.017	3238	360

Table 1: Calculated gamma-ray fluxes (column 'Flux') of gamma-ray lines characteristic for an element (col. 'El.' and 'Energy') for assumed comet composition (col. 'Concentr.'). Columns 'Time' are the required counting times to reach a preset flux error of 10 and 30 %, respectively.

Keys: d = Doppler broadening, I = inelastic neutron scattering reaction, C = neutron capture reaction, N = natural radioactivity, * = sum of two lines. [a] = photons/cm^2/min.

These investigations show that planetary gamma-ray spectroscopy has the capability to determine all major and some minor elements that form a comet and, as outlined, that the gained data provide clues to the history and origin of a comet.

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