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γ-ray spectroscopy in Mars orbit during solar proton events

M.S. Skidmore *, R.M. Ambrosi

Space Research Centre, Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH, UK

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Abstract

Understanding the evolution of Mars requires determining the composition of the surface and atmosphere of the planet. The European Space Agency's ExoMars rover mission, which is expected to launch in 2016, is part of the Aurora programme. The instruments on the rover will search for evidence of life on Mars and will map a sub-section of the Martian surface, extracting compositional information. Currently our understanding of the bulk composition (and mineralogy) of Mars relies on orbital data from instruments on-board satellites such as 2001 Mars Odyssey, Mars Reconnaissance Orbiter and Mars Express, in addition to in-situ instrumentation on rovers such as Spirit and Opportunity. γ-ray spectroscopy can be used to determine the composition of Mars, but it has yet to be successfully carried out in-situ on Mars. This study describes some of the results obtained from the γ-ray spectrometer on 2001 Mars Odyssey during solar proton events and discusses whether the increased emissions are useful in γ-ray spectroscopy. The study shows that although increased γ-ray emissions were expected from the Martian surface during a solar proton event, they were not detected from orbit probably due to insufficient signal-to-background. However, this does not preclude the possibility of measuring changes in γ-ray flux corresponding to changes in solar activity on the surface of the planet.

Keywords: Solar proton events; γ-ray spectroscopy; Mars; Composition; 2001 Mars Odyssey

1. Introduction

1.1. Planetary γ-ray emission

Particles (mainly protons and electrons) are ejected from the Sun and contribute to the solar wind. Their energies are typically in the range of eV to keV (Hundhausen, 1995), and they have speeds of approximately 400 km s^{-1} when they reach the Earth (Barnes, 1992). When the solar particles directly interact with a planetary atmosphere or surface, a complex series of interactions occur (including spallation, ionisation and absorption; these and other reactions are detailed in Krane (1988)), producing secondary particles such as neutrons and high-energy γ-rays (see Fig. 1). Similarly, galactic cosmic radiation (GCR) that is composed primarily of protons (87%) with energies ranging between 0.1 and 10 GeV/nucleon may also interact with planetary atmospheres and surfaces, thus contributing to the secondary particle fluence (Reedy and Arnold, 1972). The secondary particles created consist primarily of neutrons and γ-rays which are attenuated by the planetary surface and atmosphere. Neutron interactions with matter can include inelastic scattering or neutron capture. Boynton et al. (2004) have estimated that ~10 neutrons are produced per primary particle. The type of interaction is dependent on the neutron energy, as discussed in Masarik and Reedy (1996) and Boynton et al. (2004). The interaction of the neutron with the nucleus (via capture, inelastic scatter or non-elastic scatter) can leave the nucleus in an excited state; the de-excitation process often results in the emission of a particle or γ-ray and in some cases the re-release of a neutron at a lower energy (Kaplan, 1963). γ-ray energies can vary between 200 keV and 10 MeV (Boynton et al., 2004), and the energy of the emitted γ-ray is characteristic of the element it has been emitted from. The high-energy protons can undergo similar scattering and capture reactions with planetary surfaces and atmospheres to produce γ-rays. γ-ray emission may also

* Corresponding author. Tel.: +44 116 252 3519.
E-mail address: mss16@star.le.ac.uk (M.S. Skidmore).

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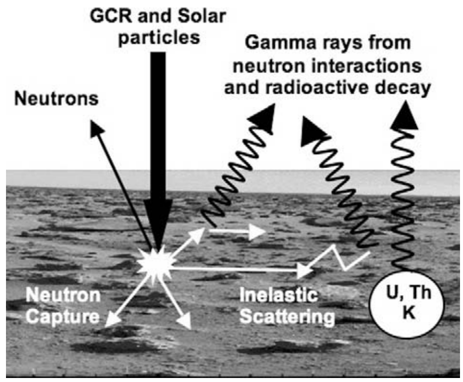

Fig. 1. Diagram showing the possible interactions of protons with a planetary surface.

occur as a result of the decay of radioactive nuclei, such as U, Th and K. A suitable γ-ray spectrometer can be used to detect the γ-rays on the surface of a planet or in orbit.

The Martian atmosphere, although thin, significantly attenuates the proton flux below 100 MeV, so few protons are able to interact with the surface (A Monte Carlo model being developed at the University of Leicester (UoL) that simulates the Martian atmosphere and surface has indicated that nearly all of the sub- 100 MeV protons are attenuated in the atmosphere, several kilometers above the surface). However, the neutrons and secondary particles created in the atmosphere via these proton reactions are able to penetrate into the surface. As a result normal solar proton emission from the Sun does not create a significant amount of γ-ray emission from the surface of Mars compared with the GCR interaction with Mars. Unlike the solar protons, the GCR protons are able to directly interact with the sub-surface because their typical energies are in excess of 100 MeV instead of keV. Typical proton fluences of GCR and solar origin detected by the space environment monitors (SEM) on the geostationary operational environmental satellites (GOES) at 1 AU are of the order of 10 protons $cm^{-2}\,sr^{-1}\,s^{-1}$ for 1–10 MeV protons, ~5 protons $cm^{-2}\,sr^{-1}\,s^{-1}$ for 10–100 MeV protons and ~1 proton $cm^{-2}\,sr^{-1}\,s^{-1}$ for >100 MeV protons (NGDC, 2008). Since the total GCR flux can be assumed to be 1–2 $cm^{-2}\,sr^{-1}\,s^{-1}$, with energies ranging from 0.1 to 10 GeV/nucleon (Reedy and Arnold, 1972), the protons >100 MeV are assumed to be of GCR origin. During a solar proton event (SPE), protons can be accelerated out from the Sun at energies >100 MeV; and the overall proton flux is enhanced. These protons will be able to directly interact with the Martian and lunar surfaces and sub-surfaces, and could lead to increased γ-ray emission from the planet. This study discusses whether this increased γ-ray emission could be exploited in order to obtain a deeper understanding of the interaction mechanisms and composition of a planetary surface.

1.2. γ-ray spectroscopy

The composition of the surface and sub-surface of a planet can be extracted from the γ-ray spectra collected, given that the γ-rays emitted by these mechanisms are element specific. In addition, the intensity of a γ-ray line is proportional to the concentration of the associated element in the surface, sub-surface or atmosphere of a planet.

γ-ray spectroscopy (GRS) can be carried out from orbit if the planetary body of interest has a thin enough atmosphere. It has been carried out in the orbit of Mars (Mars 5, Phobos 2 and 2001 Mars Odyssey, hereafter called MO) but has yet to be successfully applied in-situ (Surkov, 1997). Detection of γ-rays from orbit is dependent on the presence and density of an atmosphere. The atmospheric attenuation varies with atmospheric thickness, and the atmosphere itself will contribute to the γ-ray spectra (deconvolving an orbital γ-ray spectrum into its atmospheric and surface contributions has yet to be carried out). On the Martian surface or sub-surface the γ-ray flux can be significantly higher than that in orbit about Mars as a result of the attenuation by the atmosphere (the average count rate from the surface of Mars detected by the γ-ray spectrometer on MO is ~190 s^{-1} (Evans et al., 2007)).

A research team led by R. Ambrosi at the UoL is currently developing instrumentation for geophysical applications. The instrumentation includes a geophysical package for a future in-situ planetary science missions that can simultaneously carry out GRS, γ-ray densitometry and radiometric dating of a planetary surface. The geophysical package could be installed on a lander or (ideally) a sub-surface probe that would carry out measurements at depths of up to 5 m. The advantages, goals and challenges of a sub-surface GRS mission are detailed in Skidmore et al. (2009). Current designs for the γ-ray portion of the detector feature a lanthanum bromide ($LaBr_3(Ce)$) scintillator detector, which is compact, radiation tolerant, operates at a range of temperatures, is low in mass and has a low power requirement compared to the cooling power requirements of a high-purity germanium (HPGe) detector (Skidmore et al., 2009).

Currently the geophysical package will rely on natural γ-ray emissions caused by the proton interaction with the surface. The addition of a neutron generator could increase the surface γ-ray emission further. An increase in the γ-ray flux would reduce the accumulation time required to get a spectrum with sufficient counts in it. This was discussed in detail by Ambrosi et al. (2005). Although neutron generators are becoming more compact (e.g. a ^{252}Cf source could weigh ~ grams (Ambrosi et al., 2005)), they require shielding to protect the rest of the lander/probe, which increases the mass as well as posing a radiation hazard. The additional proton flux interacting with a planetary atmosphere, surface and sub-surface during a SPE results in an increase in the neutron flux within the surface, and an increase in the γ-ray emission from the surface. This may positively affect the counting statistics. The mechanism that creates a SPE is discussed in Section 1.3.

1.3. Solar proton events

A SPE refers to an enhancement in solar proton emissions from the Sun, but generally speaking these events