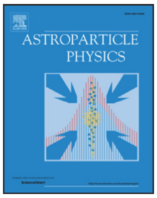
Astroparticle Physics 98 (2018) 28–37

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys



Measuring the Galactic Cosmic Ray flux with the LISA Pathfinder radiation monitor

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ARTICLE INFO

Article history:
Received 20 November 2017
Revised 12 January 2018
Accepted 17 January 2018
Available online 31 January 2018

ABSTRACT

Test mass charging caused by cosmic rays will be a significant source of acceleration noise for space-based gravitational wave detectors like LISA. Operating between December 2015 and July 2017, the technology demonstration mission LISA Pathfinder included a bespoke monitor to help characterise the relationship between test mass charging and the local radiation environment. The radiation monitor made in situ measurements of the cosmic ray flux while also providing information about its energy spectrum.

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https://doi.org/10.1016/j.astropartphys.2018.01.006
0927-6505/

Keywords:
LISA
Pathfinder
GCR
Radiation Monitor
GEANT4
Charging

We describe the monitor and present measurements which show a gradual 40% increase in count rate coinciding with the declining phase of the solar cycle. Modulations of up to 10% were also observed with periods of 13 and 26 days that are associated with co-rotating interaction regions and heliospheric current sheet crossings. These variations in the flux above the monitor detection threshold (≈ 70 MeV) are shown to be coherent with measurements made by the IREM monitor on-board the Earth orbiting INTEGRAL spacecraft. Finally we use the measured deposited energy spectra, in combination with a GEANT4 model, to estimate the galactic cosmic ray differential energy spectrum over the course of the mission.

1. Introduction

Launched in December 2015 and operated until mission completion in July 2017, LISA Pathfinder (LPF) was a European Space Agency mission that successfully demonstrated the feasibility of building a future space-based gravitational wave observatory [1]. As currently envisaged, an observatory like the proposed Laser Interferometer Space Antenna (LISA) will involve placing test masses on-board distant spacecraft in near perfect free-fall while using laser interferometry to measure their relative acceleration [2]. At low frequencies a variety of local forces can produce spurious acceleration noise and limit the sensitivity of the detector. One such disturbance results from the noisy accumulation of charge on the free-floating test masses due to the high-energy ionising radiation present in the space environment. Such charging has been shown to be a significant source of acceleration noise at frequencies below 1 mHz [3].

The Pathfinder orbit around the L1 Lagrange point placed it outside Earth's protective magnetosphere and exposed it to the interplanetary charged particle environment. To contribute to test mass charging particles needed to be of an energy sufficient to penetrate the spacecraft and outer housing with simulation predicting this cut-off to be around 100 MeV for protons [4,5].

The test mass charging rate itself is dependent on both the flux and energy spectrum of the incident radiation. However, if either of these are modulated, for example by fluctuations in the Interplanetary Magnetic Field (IMF), it can lead to excess charging noise above the expected flat Poissonian spectrum. This outcome is fairly intuitive in terms of the incident flux while for a modulated energy spectrum one needs to consider that due to higher charge multiplicity, charging from high-energy particles is more noisy than charging from lower energy particles [4].

In order to better understand the relationship between test mass charging and the local radiation environment the Pathfinder payload included a bespoke radiation monitor. Its purpose was to make *in situ* measurements of the flux while also providing information about the energy spectrum of the incident radiation.

2. The interplanetary charged particle environment

Above the 100 MeV boundary relevant for Pathfinder there are two main sources of interplanetary charged particle that dominate test mass charging. Forming a permanent background, the first originate from outside the solar system and are referred to as Galactic Cosmic Rays (GCRs). These primarily consist of protons but also contain a significant fraction of helium nuclei (α-particles) as well as a small fraction of heavier nuclei. The precise ratios vary at lower energies but above several GeV approximately 80% of primary nucleons are free protons and about 70% of the rest are bound in helium nuclei [6]. At lower energies, measurements within the heliosphere have shown that the GCR background fluctuates over various time-scales with changes over the 11-year solar cycle being most significant.

A common way of understanding these modulations is to assume an isotropic, steady-state flux at the heliosphere boundary, referred to as the local interstellar spectrum (LIS). This flux of particles then interacts with the solar wind and IMF as it penetrates deeper within the heliosphere with variations in the heliospheric properties therefore leading to the observed temporal changes in the GCR spectrum. The change in flux is strongly dependant on the energy of the particle with those at around 100 MeV varying by orders of magnitude while the flux of particles above about 10 GeV being almost constant.

Given the difficulty in measuring it directly, the LIS has historically been inferred from measurements made within the heliosphere although in recent years Voyager 1 has begun providing *in situ* measurements [7]. Several expressions that describe the LIS for protons and α-particles can be found within the literature but throughout this paper we will use those described by Bisschoff and Potgieter [8] which are based on combined Voyager 1 and PAMELA measurements:

$$J_{LIS_p}(T) = 3719.0\frac{1}{\beta^2}T^{1.03}\left(\frac{T^{1.21}+0.77^{1.21}}{1+0.77^{1.21}}\right)^{-3.18} \tag{1}$$

$$J_{LIS_\alpha}(T) = 195.4\frac{1}{\beta^2}T^{1.02}\left(\frac{T^{1.19}+0.60^{1.19}}{1+0.60^{1.19}}\right)^{-3.15} \tag{2}$$

where T is the kinetic energy (GeV/nucleon), $\beta = v/c$ is the particles velocity relative to the speed of light and $J_{LIS}(T)$ is in units of (particles/(m^2 sr s GeV/nucleon)). The time dependant differential intensity J_i of nucleus of type i at 1 AU can then be parameterised by the "force-field" approximation [9–11]:

$$J_i(T,\phi) = J_{LIS,i}(T+\Phi)\frac{(T)(T+2T_r)}{(T+\Phi)(T+\Phi+2T_r)} \tag{3}$$

where T_r is the rest mass (GeV/nucleon), $\Phi = (Ze\cdot 10^{-3}/A)\phi$, Z is the atomic number, e is the elementary charge, A is the mass number and ϕ is the modulation potential (MV). The parameter ϕ has limited physical meaning and is implicitly dependant on the fixed shape of the LIS chosen. However, it offers a simple way of describing both the proton and α-particle differential energy spectra incident on the Pathfinder spacecraft using just a single parameter. Fig. 1 illustrates the relationship between the above LIS and ϕ, where ϕ takes values of 400 & 600 MV which were the values at either extreme of the fluxes observed during the Pathfinder mission (as we shall see in Section 6).

The second source of charged particles above 100 MeV are those shock accelerated near the Sun during coronal mass ejections, referred to as Solar Energetic Particles (SEPs). These transient solar eruptions are more frequent around solar maximum, with on average a few a year energetic enough to enhance test mass charging, but less than one a year at solar minimum. Their properties are event specific but can temporarily increase the proton flux by several orders of magnitude for durations spanning hours up to several days [5,12,13]. Given the Pathfinder mission was to be operational for around 18 months during the declining phase of the solar cycle, pre-flight predictions were for at most one solar event energetic enough to enhance test mass charging [14].