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Parameterization of galactic cosmic-ray fluxes during opposite polarity solar cycles for future space missions

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Abstract: Galactic cosmic-ray (GCR) long-term variations and short-term fluctuations affect observations on board long-lived space missions. We have developed a parameterization of proton and helium fluxes for various levels of solar modulation during opposite polarity periods on the basis of experimental data. In spite of a general agreement among different results on p, $\overline{p}$, e^+ and e^-, some contradictory clues have been found both at solar minimum and maximum during negative polarity periods (A<0). We illustrate the implications of the results of this work for and with missions like LISA (Laser Interferometer Space Antenna).

Introduction

Solar activity, the drift of opposite charge particles in the Global Solar Magnetic Field (GSMF) and interplanetary processes affect cosmic-ray observations. Balloon-borne and space experiments are mainly interested by long-term variations [1] . For missions like LISA, aiming at the detection of low-frequency gravitational waves in space, energetic solar and galactic cosmic rays constitute major sources of noise. In particular, short-term GCR fluctuations generate spurious signals in the experiment band and SEPs associated with strong solar events overcome the whole mission noise budget [2]. A real-time monitoring of incident solar and GCR will be carried out on board LISA and its precursor mission LISA-PF [3]. Radiation Monitor (RM) measurements will give precious contributions to solar and cosmic-ray physics investigations [4]. In order to disentangle the role of solar particles and of various interplanetary processes, in this work we report the results of a study of long-term cosmic-ray variations based on data gathered during the last two solar cycles. In particular, we have carried out proton and helium flux parameterization as a function of solar modulation during opposite polarity epochs at 1 AU. Implications for the LISA missions are presented (see also [4]).

Solar modulation and solar polarity effects on GCR

Long-term cosmic-ray variations are correlated with the 11-year solar cycle and the 22-year GSMF polarity reversal. The symmetric model in the *force field approximation* by Gleeson and Axford [5] allows us to estimate the cosmic-ray spectrum at a distance r from the Sun, at a time t when the time independent interstellar intensity is given. An energy loss related to cosmic-ray particle charge and a $solar\ modulation\ parameter$ (ϕ) above about 100 MeV are assumed. This simple model does not take into account the GSMF polarity influence on the drift of positive and negative particles in the heliosphere. During positive (A>0) heliomagnetic field polarity, positive charge particles reach the Earth most likely from the polar regions of the heliosphere, while negative charge particles (e^-,$\overline{p}$) come mainly from the ecliptic regions along the Heliospheric Current Sheet (HCS). An opposite situation holds during negative magnetic field polarity epochs. Particle fluxes propagating along the HCS are more modulated with respect to those coming from the poles. At solar minimum drift effects have been observed to determine a maximum reduction of the galactic cosmic-ray proton and helium fluxes during a negative polarity epoch of 40% at 100 MeV, 30% at 200 MeV, 25% near 1 GeV and of a few % up to 4 GeV [6]. At solar maximum the drift process is found to be ineffective by Boella et al. [6] but large fluctuations in the opposite charge particle ratio are observed before and after polarity change (see for example [7]).

Cosmic-ray observations during the last two solar cycles

Protons and electrons constitute the most abundant positive and negative components of cosmic rays, respectively. The study of proton flux and $e^+/(e^+{+}e^-)$ ratio during different solar cycles allow us to limit the role of statistical errors.

Protons and helium nuclei

In fig. 1 we have reported the BESS and BESS-TeV experiment proton and helium (scaled of a factor of 10) data gathered between 1997 and 2002 [8]. This interval of time spans from solar minimum during a positive polarity period (1997) to solar maximum during a negative polarity epoch (2002). The polarity change $+/-$ occurred in 2000. In order to cover a larger period of observations for protons we have added data gathered during a negative polarity epoch at solar minimum (LEAP87; [9]) and solar maximum in slightly different conditions with respect to BESS02 (MASS89; [10]). In [8] the Gleeson and Axford model has been applied to the BESS data for each flight. The proton flux at the InterStellar Medium (ISM) used in their work is reported as the top continuous line in fig. 1. We have reproduced the Shikaze et al. results. We have applied the same model to the LEAP87 and MASS89 experiments as well. The solar modulation parameters (ϕ) for all flights appear in the same figure. A good agreement is found below a few GeV among the modulated ISM Shikaze et al. proton flux and the BESS data gathered in positive polarity and at polarity change while the measurements carried out at solar maximum during negative polarity periods differ from the model predictions at the same energies. The LEAP87 and BESS97 data gathered during opposite solar polarity epochs at solar minimum do not show any significant difference. This evidence contradicts the Boella et al. results. In order to clarify this scenario we draw our attention to electron and positron observations.

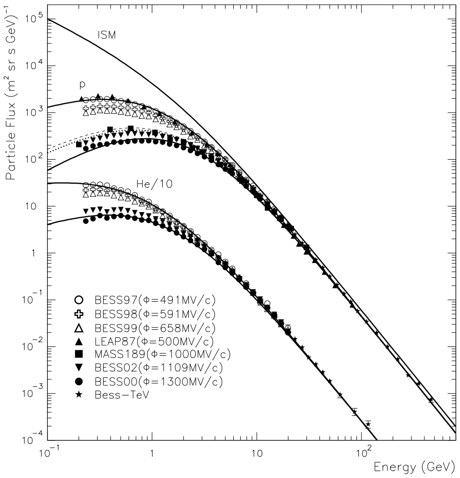

Figure 1: GCR proton and helium (scaled as indicated) flux measurements carried out during the last two solar cycles. See text for details.

Electrons and Positrons

In fig. 2 we have reported the $e^+/(e^+{+}e^-)$ ratio measurements carried out during the last fifteen years. Open and closed symbols indicate positive and negative polarity periods, respectively. These observations are consistent with a pure secondary e^+ origin below a few GeV if the ISM e^+ and e^- flux calculations by Moskalenko and Strong [11] are considered and the solar modulation, including drift, is taken into account. Thick dot-dashed curves 1 and 2 in fig. 2 correspond to solar minimum, negative and positive polarity periods, respectively. Curve 3 represents the upper limit to the

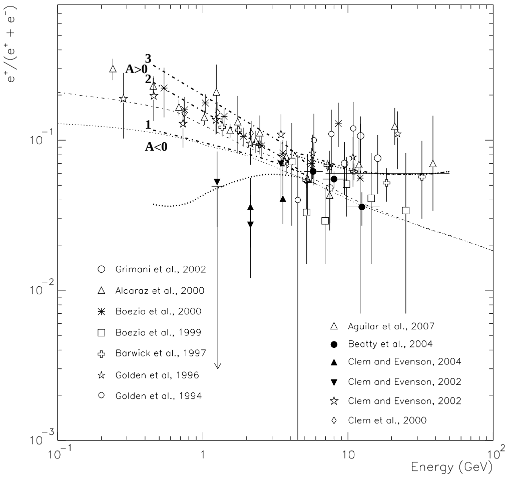

Figure 2: Positron fraction measurements (references to data and figure details are reported in [1]).

positron fraction in positive polarity. These curves have been determined on the basis of the Boella et al. and Moraal, Jokipii and Mewaldt experimental results. The thick dotted curve has been estimated on the basis of the Moskalenko et al. [12] proton and antiproton calculations at solar polarity +/- change. These calculations are found in good agreement with the BESS antiproton data. In conclusion, we observe that positron and the majority of other particle observations present an analogous trend as a function of the overall solar modulation. The HEAT data (open crosses and solid dots in fig. 2) gathered above a few GeV during opposite polarity periods, do not present any major difference. However, in this energy range the solar modulation is not supposed to play an important role.

Proton and helium flux parameterization

We have interpolated proton and helium flux measurements using the function reported in eq. 1 (see also [13]).

$$F(E) = A(E+B)^{-\alpha} E^{\beta} Part./(m^2 srs GeV) \tag{1}$$

Experiment	A	B	α	β
p (BESS97)	18000	1.09	3.66	0.87
p (BESS00)	18000	1.71	4.20	1.41
p (MASS89)	18000	1.57	3.95	1.16
p (BESS02)	18000	1.60	3.99	1.20
He (BESS97)	850	0.915	3.17	0.42
He (BESS00)	850	1.25	3.60	0.85

Table 1: Proton (p) and helium (He) flux parameterization for different solar modulation and polarity condition measurements.

Where E is in GeV and the parameters A, B, α, β appear in Table 1 for different proton and helium flux measurements. Results appear in fig. 1 for BESS97 (solar minimum; positive polarity) and BESS00 (solar maximum; $+/-$ polarity change) as thick continuous lines. We stress that our parameterization reproduces the proton BESS-TeV data above a few GeV better than the ISM spectrum chosen in [8]. In the same figure the dashed and dotted lines indicate the proton flux parameterization for the MASS89 and BESS02 experiments reported in Table 1.

The low-energy part of these last two data sets differ from the given parameterization found to work very well for positive polarity period data. We have estimated the flux average reduction factor, R(E), for the two flights due to the polarity effect near solar maximum (eq. 2) as a function of the energy. The proton and helium flux reduction at solar minimum on the basis of the Boella et al. results has been parameterized as well (eq. 3).

$$R(E) = 0.61 + 1.41E - 1.2E^{1.32} + 0.146E^{1.95} \tag{2}$$
$$0.1 \le E(GeV) \le 1.6$$

$$R(E) = 1 + \frac{0.4}{1.602}\log E + \frac{0.4}{1.602} - 0.4 \tag{3}$$
$$0.1 \le E(GeV) \le 4.0$$

Long-term cosmic-ray variation observations on board the LISA missions

LISA consists of three spacecraft placed 5×10^6 km apart at the corners of an equilateral triangle. Each spacecraft hosts two inertial sensors.

	Positive Polarity	Negative polarity
LISA-PF	1334	1292
LISA	3349 (sol. min.)	1029 (sol. max.)

Table 2: Expected integral proton flux [Part (m^2 sr s)$^{-1}$] at the time of the LISA missions.

The heart of the inertial sensors are cubic gold-platinum test masses. The test masses constitute the interferometer mirrors. Their position is detected with gold plated electrodes. Energetic solar and cosmic rays charge the test masses generating spurious signals. Two silicon wafers of 1.4 x 1.05 cm^2 area placed in a telescopic arrangement will monitor the overall incident cosmic-ray flux on board. The geometrical factor of each silicon layer for an isotropic incidence is 9 cm^2 sr and for coincidence events is about one tenth of it. LISA-PF (one spacecraft) will be placed in orbit in L1 by the end of 2009 and it will gather science data between March and September 2010 near polarity change from - to +. We expect a solar modulation parameter, ϕ, during the mission of 1100 MV/c. Integral proton and helium fluxes measured by BESS02 can be reasonably used as input fluxes for LISA-PF in positive polarity. In case of negative polarity the input fluxes must be reduced as indicated in eq. 2.

LISA is supposed to be launched in 2018 during a positive polarity period at solar minimum. The spacecraft formation center of mass will lie on the ecliptic plane, 50×10^6 km behind the Earth. The maximum duration planned for the mission is ten years during the 25 solar cycle. The proton integral fluxes at the time of LISA-PF and LISA are reported in Table 2. We have estimated an increase of about 80% of the test-mass charging from LISA-PF to LISA. An increase of 60% on the radiation monitor countrate is expected as well.

Conclusions

We have carried out a parameterization of proton and helium fluxes at solar minimum and maximum during different solar polarity epochs. Implications for the LISA missions have been studied.

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