IONS ABUNDANCE CLOSE TO THE EARTH SURFACE:
THE ROLE OF THE MAGNETOSPHERE

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We have compared the data of protons and helium from the AMS-01 detector in the energy range 0.1-200 GeV, and heavier ions (from Z=4 to Z=28) from the HEAO-3-C2 in the energy range 0.6-35 GeV/n. Data have been collected almost in the same solar period and the same polarity (1980 for HEAO and 1998 for AMS-01). The experimental conditions are also comparable: altitude and inclination of the orbit, angular acceptance of the detectors. The effect of magnetosphere is to introduce a rigidity cut-off. The results are that the abundance ratio of nuclei/protons is larger than what expected from the spectra measured outside the magnetosphere. We discuss this effect in relation to what has been observed in experiments on board of satellites orbiting near the Earth surface.

1. Introduction

Apart from particles generated during the solar flares, the measured cosmic radiation comes from outside the solar system. This component, the Galactic Cosmic Rays (GCR), is dominant at energy higher than few hundreds MeV, but is modulated by the solar activity inside the heliosphere up to few GeV. Protons are largely the most abundant component of this radiation (≈ 87%)\(^1\). Nevertheless to GCR contribute also electrons, ions (all the stable nuclei), and a small fraction of antimatter of secondary origin.

The problem of evaluating both the absolute and the relative abundance of the Cosmic Rays (CR) is very important in relation to the radiation damage and radiation dose in space. An accurate evaluation of these quantities is even more important in prevision of the long duration space missions

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already scheduled, like the International Space Station (ISS), a permanent orbiting station at an altitude of 400 km, or the planned manned interplanetary flights. The effect of radiation on both electronics stuff and organic tissue is depending on the absolute rate of CR, but it is related also to the relative abundance of ions$^{2-4}$.

![Figure 1. Differential Energy spectra of Cosmic Rays. Data of $p$ and $He$ come from AMS-01, data of $C$ and $Fe$ come from HEAO-3-C2.](image)

Current estimates are based on measurements performed by several satellites during the last 30-40 years, most of them operating outside the magnetosphere$^5$. The abundance of different particles or nuclei is usually described in relation to the kinetic energy, which is the natural parameter in the free propagation space. The total intensity of primary nucleons in the energy range from several GeV to the TeV and beyond is approximately given by$^{1,5}$:

$$I_\alpha(E) \sim 1.8 \ E^{-\alpha} \ \text{nucleons cm}^{-2} \text{ s sr GeV}$$

where $E$ is the energy per nucleon and $\alpha \approx 2.7$ is the differential spectral index of the Cosmic Ray flux. The fraction of the several components is approximately constant, as shown in Figure 1. When CR enter into the magnetosphere the Earth magnetic field provides a shield against the penetration of CR down to the Earth surface. The result is a rigidity cut-off below which CR can not penetrate. Therefore inside the magnetosphere the natural parameter to deal with is the rigidity (see Figure 2).
Figure 2. Differential Rigidity spectra of Cosmic Rays. Data of \( p \) and \( He \) come from AMS-01, data of \( C \) and \( Fe \) come from HEAO-3-C2.

2. Data set and detectors

We have evaluated CR measurements inside the magnetosphere. We considered the data of protons and helium from the AMS-01 detector in the energy range \( 0.1 - 200 \text{ GeV} \), and heavier ions (from \( Z = 4 \) to \( Z = 28 \)) from the HEAO-3-C2 in the energy range \( 0.6 - 35 \text{ GeV/n} \). Data have been collected almost in the same solar period and the same polarity: 1979-80 for HEAO; and June 1998 for AMS-01. The experimental conditions are also comparable. The altitude is \( \approx 380 \text{ km} \) for AMS-01 and \( \approx 500 \text{ km} \) for HEAO-3; the inclination of the orbit is 51.6 deg for AMS-01 and 43.6 deg for HEAO-3; the angular acceptance of the detector is a cone of \( \approx 32 \text{ deg} \) from the axis for AMS-01 and \( \approx 28 \text{ deg} \) for HEAO.

The Alpha Magnetic Spectrometer (AMS)\(^6\) had a precursor flight (AMS-01) on board of the space shuttle Discovery (flight STS-91), lasting 10 days, from June 2 to 12, 1998. AMS-01 has been the first magnetic spectrometer in space with large collecting area (\( \approx 1 \text{ m}^2 \)). AMS-01 has provided detailed measurements of charged particles flux outside the Earth’s atmosphere, collecting \( \approx 10^7 \) protons in the energy range \( 0.1 - 200 \text{ GeV} \), \( \approx 10^6 \) electrons in the energy range \( 0.2 - 30 \text{ GeV} \) and \( \approx 10^6 \) helium nuclei in the energy range \( 0.1 - 100 \text{ GeV/nucleon} \).

The HEAO-3\(^7\) (High Energy Astronomical Observatory) mission performed a sky survey of gamma rays and cosmic rays. The scientific objectives of the experiment HEAO-3-C2 were the determination of the isotopic composition of the most abundant components of the cosmic-ray flux with
atomic mass between 7 and 56, the measurement of the flux of each element with atomic number (Z) between \( Z = 4 \) and \( Z = 50 \), and the search for super-heavy nuclei up to \( Z = 120 \). The normal operating mode was a continuous celestial scan around the Z axis (nominally pointed towards the sun). The satellite has been launched in September 1979. The data used here, and shown in Figures 1 and 2, covers the period from October 1979 to June 1980.

3. **CR fluxes inside the magnetosphere**

The effect of the magnetosphere, the region where the Earth magnetic field is present, on CR can be described in terms of the gyroradius or, better, of the magnetic rigidity \( R \): \( R = pc/Ze \). A particle with a rigidity lower than a threshold value (usually called rigidity cut-off) can not go beyond the magnetosphere and reach the Earth surface. The value of the rigidity cut-off is position dependent, in particular it is decreasing going towards the magnetic poles.

![Figure 3. Rigidity spectra of Cosmic Rays inside the magnetosphere. We have considered two geomagnetic regions, M1 and M5, as defined by AMS-01.](image)

We have computed the probability for a CR to penetrate the magnetosphere and be detected. We have considered the AMS-01 geomagnetic regions (M). We have then computed the flux of primary CR entering each geomagnetic region, according to the measurements of AMS-01. For instance in Figure 3 we present the flux of \( p \) and \( He \) for the geomagnetic
regions $M_1$ and $M_5$, at low and medium geomagnetic latitude respectively. For the same geomagnetic region $M$, the flux cut-off in both $p$ and $He$ measured spectra occurs at the same value of rigidity $R$, as shown in Figure 3. This is a further confirmation that inside the magnetosphere the rigidity represents the natural parameter describing CR spectra.

4. Abundance calculations

We have computed the abundance ratio of Helium, Carbon, Iron, respect to protons. We have considered that at a certain position inside the magnetosphere all the particles above the rigidity cut-off are present. Therefore the ratio has been computed using the integral flux above the quoted value. The results are shown in Figure 4. We can compare the flux ratio in rigidity (Figure 4 - right panel), corresponding to what we can measure inside the magnetosphere, with the flux ratio in energy (Figure 4 - left panel), corresponding to the cosmic abundances.

![Figure 4. Integral flux ratio of $He/p$ (●), $C/p$ (▲), $Fe/p$ (▼), versus kinetic Energy (left panel) and Rigidity (right panel).](image)

Table 1. Comparison of the integral flux ratio of $He/p$, $C/p$ and $Fe/p$ in kinetic Energy and Rigidity.

<table>
<thead>
<tr>
<th></th>
<th>kinetic energy</th>
<th>rigidity</th>
<th>increasing factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$He/p$</td>
<td>$6 - 5 \times 10^{-2}$</td>
<td>$9 - 18 \times 10^{-2}$</td>
<td>$1.5 - 3.6$</td>
</tr>
<tr>
<td>$C/p$</td>
<td>$1.8 - 2.5 \times 10^{-3}$</td>
<td>$3.6 - 5.3 \times 10^{-3}$</td>
<td>$2.0 - 2.1$</td>
</tr>
<tr>
<td>$Fe/p$</td>
<td>$1.8 - 3.5 \times 10^{-4}$</td>
<td>$3.7 - 10 \times 10^{-4}$</td>
<td>$2.0 - 2.8$</td>
</tr>
</tbody>
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The flux ratios, evaluated both in energy and rigidity (see Figure 4),
of ions/protons is roughly constant, apart Fe/p ratio which looks slightly increasing with the rigidity (or the energy). As it can be observed in Figure 4, and shown in Table 1, the flux ratio is enhanced when evaluated in rigidity by a factor going from $\sim 2$ to $\sim 3$.

5. Conclusions

It is important to evaluate both the absolute and the relative abundance of the Cosmic Rays in relation to the radiation damage and radiation dose in space. Besides, inside the magnetosphere we need to consider the ions abundance in terms of rigidity instead of kinetic energy. When the flux ratio is evaluated inside the magnetosphere (in rigidity) its value is enhanced by a factor going from $\sim 2$ at low energy to $\sim 3$ at high energy. For instance the cosmic $He/p$ ratio is $\simeq 5 \times 10^{-2}$, but inside a geomagnetic region like M1 (for a rigidity $\geq 10$ GV) we obtain $He/p \simeq 0.18$. The final result is that the fraction of ions in the magnetosphere is at least 2—3 times larger than what is usually quoted as the cosmic abundance$^{10}$. This result must be considered when the effects of cosmic radiation on orbiting satellites are evaluated. This effect is easily understood. In fact when we compute the abundance ratio in terms of rigidity instead of kinetic energy we need to take into account that the nuclear charge over mass ratio is $Z/A \simeq 1/2$ for almost all the nuclei except the $H$ for which the ratio is $Z/A \simeq 1$.

References