A method to detect positron anisotropies with Pamela data


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Abstract

The PAMELA experiment is collecting data since 2006; its results indicate the presence of a large flux of positron with respect to electrons in the CR spectrum above 10 GeV. This excess might also be originated in objects such as pulsars and microquasars or through dark matter annihilation. Here the electrons and positrons events collected by PAMELA have been analyzed searching for anisotropies. The analysis is performed at different angular scales and results will be presented at the conference.

Keywords: PAMELA, cosmic ray, anisotropy, positron, electrons

Introduction

Recently, the Fermi and AMS experiments [1, 2] have confirmed the PAMELA data on the positron fraction in cosmic rays (CRs). In 2009, PAMELA measurements showed the positron fraction – i.e., the $e^+/(e^-+e^+)$ flux ratio – to increase steadily for primary CRs with energy from 10-200 GeV [3]. CRs at GeV-TeV energies are thought to be Galactic because they can be produced in supernova remnants (SNRs) within the Milky Way; they diffuse through the Galaxy scattering off random inhomogeneities of the Galactic magnetic field. The positron excess can not be explained by a diffusive propagation model that only considers secondary positrons [4, 5], but a new additional CR source is required. Two popular hypotheses concern the existence of $a$) a nearby astrophysical source, e.g., a pulsar or a SNR [6]; or $b$) an astroparticle source, e.g., the products of dark matter annihilation.
ter (DM) decay or annihilation. In the latter case it may be possible to search in a definite direction: some DM models \[7, 8\] predict a significant fraction of positrons produced in the decay/annihilation of particles near the Sun.

Considering particle energies and the Galactic Magnetic Field (GMF) magnitude, we expect a large isotropy in the distribution of arrival direction of CR electrons and positrons. It is reasonable to suppose that the presence of an additional source can produce structure with definite angular width in the detected data. As PAMELA is set on the Resurs-DK1 satellite, it has a relatively uniform exposure over the celestial sphere, allowing the analysis on anisotropies in each angular window of the sky.

1. The PAMELA detector

The PAMELA experiment has been operating on board of the satellite Resurs DK1 since 2006 June; its orbit, 70° inclination and 350 ÷ 610 km altitude, allows PAMELA to perform a very detailed measurement of the cosmic radiation in different regions of the Earth’s magnetosphere. PAMELA’s goals include studies of matter and antimatter in primary CRs from a few tens of MeV to a few hundreds of GeV, and studies of solar physics. In particular, PAMELA has collected a considerable number of electrons and positrons, whose analysis is described in several publications \[3, 10, 11\].

The PAMELA detector \[12\] is equipped with a magnetic spectrometer, i.e., a permanent magnet that hosts a tracking system. The tracking system consists of six double-sided micro-strip silicon sensors, which allow the determination of the particle charge and rigidity (momentum/charge) with high precision. An imaging electromagnetic calorimeter, made of 44 silicon planes interleaved with 22 plates of tungsten absorber, is mounted below the spectrometer to accurately measure the energy loss. A Time of Flight (ToF) system made of three planes of double layer of plastic scintillator allows measurements of particle velocity and energy loss and also provides the main trigger for the experiment. A neutron detector, placed below the calorimeter, gives additional information about the shower extension and improves lepton/hadron discrimination. In addition, an anti-coincidence system rejects particles due to scattering or interactions inside PAMELA.

For each particle crossing the detector, the arrival direction from space is reconstructed using the trajectory inside the instrument and the satellite position on the orbit, providing for electrons and positrons an accuracy of about 2 degrees over the whole energy range.

2. Analysis Method

In order to identify any nearby source of positrons, an analysis of the distribution of arrival directions of CRs detected by PAMELA is performed. The method has been developed as indicated below:

1. a sample of CR electrons and positrons has been selected, creating the map of the events detected by PAMELA;
2. the expected background from different sky directions under the assumption of an isotropic flux has been calculated, obtaining the ‘background sky map’;
3. to highlight the presence of any large scale pattern in the dataset, the signal and the background have been compared with two independent and complementary techniques, the statistical significance test introduced by Li-Ma \[16\] and the spherical harmonic analysis.

2.1. Data

To use the same events analysed by \[10\], the dataset we used refers to the period from launch (June 2006) to the solar minimum (2010). The same track and event quality selection as in \[11\] have been used; the hadron contamination was instead reduced to a negligible amount by using a stronger calorimeter selection (with about 80% selection efficiency) combined with the condition of the detection of less than three neutrons by the neutron counter. In the energy range from 10 to 200 GeV, we have selected 19184 electrons and 1489 positrons. Finally, a further analysis on the satellite orientation has been carried on by comparing the pointing of the detector with offline rotation tables used by the host satellite camera to take pictures of the Earth. This refined analysis permitted to minimize the uncertainty of the measured absolute incoming trajectory for all the selected particles.

To display the arrival direction distribution over the whole sky, the Healpix framework, which provides a visualization of the sky map in a 2D-sphere \[15\], is used. This tool produces a subdivision of the 2D-sphere in which each pixel covers the same surface area as other pixels and is regularly distributed on lines of constant latitudes. In the Healpix scheme the pixel size depends on the total number of pixel map, which is given by \(12 \times n_{side}^2\) where \(n_{side}\) defines the map resolution and can take only a value that is power of 2. For this survey we have adopted the galactic coordinates with a grid...
of 3072 pixels, corresponding to an angular pixel extension of about $\sim 7^\circ$. In Fig. 1 are reported the maps obtained for the selected positrons and electrons with energy greater than 10 GeV.

2.2. Background Estimation

To underline the presence of any structure, the event map must be compared with the background map that corresponds to the null anisotropy hypothesis. The latter represents the expected number of events in each direction of the sky, under the assumption of an isotropic flux. For its determination, the precise knowledge of the directional exposure of the detector is fundamental, because inaccuracies in calculating exposures in different directions of the sky, in dead-time estimation, or in accounting of other detector effects may cause fake anisotropies in the measured arrival direction distribution. In this case the most commonly used technique is the shuffling method [13], which allows the construction of the background starting from data itself.

In this case, different data sets are simulated and the final background map corresponds to the averaged one. Each artificial simulated data set is obtained combining the coordinates (arrival direction) of an event in the instrument local frame with the arrival time of another event, randomly selected. Using the time dependent conversion from local to Galactic coordinates to obtain the celestial coordinates of the events, each simulated data set preserves the local arrival direction distribution and the detector acceptance.

In this survey the shuffling procedure is repeated $O(10^3)$ times and in Fig. 2 is reported the background map obtained averaging the $10^3$ electron shuffled maps.

![Figure 1: Map of the positrons and electrons detected by PAMELA and selected in the period 2006-2010 for $E > 10$ GeV.](image1)

![Figure 2: Map of the shuffled electrons detected by PAMELA and selected in the period 2006-2010 for $E > 10$ GeV. The map is the mean of the $10^3$ electron shuffled maps.](image2)

2.3. Integration

As PAMELA had a shorter exposure to the poles, the sky was not observed uniformly, leading to a particular shape in the no-anisotropy map. Since the anisotropy signal is weak, we need to consider the bin angular size. Both the signal and the coverage maps are produced with independent bins, but this procedure can spread signal over multiple adjacent bins, making the measurement more difficult. Since to highlight a possible anisotropy the bin size must be similar to the angular scale of the anisotropy itself, to increase sensitivity it is possible to use integrated bins, where the content of each bin is equal to the integrated number of events in a circular region around itself.

The radius chosen for the integration represents the angular scale at which the anisotropy is expected since the sensitivity for detecting an anisotropy with a given angular scale increases by choosing an integration radius close to its scale. Indeed, if the integration radius is too small the signal is distributed among adjacent bins, while if it is too large we integrate too much background which swamps the anisotropy. The event and coverage
maps have been integrated over the following angular scales: 10°, 30°, 60°, 90°. The corresponding results are reported in Fig. 3 for positrons and in Fig. 4 for the shuffled electrons.

3. Significance Maps

To estimate the statistical significance of any excess or deficit we used the method suggested by Li and Ma in 1983 [16], which applies the likelihood functions both to the null hypothesis and to the signal; the ratio between these two functions represents the significance of the excess (or deficit), as

\[
S = \pm \sqrt{2} \left\{ N_{\text{on}} \ln \left( 1 + \alpha \left( \frac{N_{\text{on}}}{N_{\text{on}} + N_{\text{off}}} \right) \right) \right. \\
+ N_{\text{off}} \ln \left( 1 + \alpha \left( \frac{N_{\text{off}}}{N_{\text{on}} + N_{\text{off}}} \right) \right) \right\}^{1/2}
\]

where \( N_{\text{on}} \) and \( N_{\text{off}} \) are respectively the observed and the expected number of events in a certain angular window of the sky. of the sky, and \( \alpha \) is the on-source to off-source exposure ratio (in our case \( \alpha = 1 \)).

The significance is defined as positive if there is an excess and negative in the presence of a deficit of events. With these assumptions, in the absence of any signal, the significance \( S \) can be considered asymptotically drawn from the normal distribution with zero mean and unit variance, expressing the result as the number of standard deviation.

Significance maps, constructed by comparing signal and background maps in pairs for the different integration radii, are reported in Fig. 5.

In Fig. 6 the histograms report the obtained significance and the fit with a Gaussian function; no significant deviation from the isotropy is observed. It can be seen that the significance distribution becomes sharper by increasing integration radius, due to the fact that with larger integration radius, the bins are strongly correlated, reducing the variance of the distribution.

4. Conclusions

We have presented a method to study the positron anisotropies with PAMELA data and we have applied it to a dataset of electrons and positrons, selected in the period 2006-2010. No anisotropy have been highlighted for the positron fraction \((e^+/(e^+ + e^-))\) for the different angular scales considered.

References

Figure 3: Event maps for E>10 GeV, over the following angular scales: 10°, 30°, 60°, 90°

Figure 4: Coverage maps for E>10 GeV, over the following angular scales: 10°, 30°, 60°, 90°
Figure 5: Significance maps for E>10 GeV, over the following angular scales: 10°, 30°, 60°, 90°

Figure 6: Histograms for the significance maps for E>10 GeV, over the following angular scales: 10°, 30°, 60°, 90°