Origin of cosmic-ray positrons

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***Abstract*. PAMELA measurements of the $e^+/(e^+ + e^-)$ ratio confirm, on average, the trend of previous, most accurate observations up to 50 GeV. Secondary e^+ dominate up to 10 GeV. Between 10 GeV and 50 GeV the magnetosphere of galactic middle aged pulsars appears to be the most plausible source of positrons in addition to secondary particles. Above a few tens of GeV an agreement with this scenario can be claimed within experimental and theoretical errors. However, an additional component of positrons might be considered above 50 GeV on the basis of the PAMELA data point trend. We have estimated this possible extra positron component. Reasonable scenarios are considered to explain observations.**

***Keywords*: Cosmic rays- Sun: solar-terrestrial relations - Stars: pulsar: general**

I. INTRODUCTION

Cosmic-ray positrons are mainly produced in proton and nucleus interactions in the interstellar medium (see for example [1] and references therein). However, on average, measurements above a few GeV indicate an e^+ excess with respect to the estimated secondary component [2].

Among all suggested extra origins for positrons, pair production in the pulsar magnetosphere appears to be one of the most promising [2], [3], [4]. We estimated the average parameters of mature pulsars (magnetic field and period) consistent with the assumption of e^+ and e^- production at the pulsar polar cap in addition to the secondary component ([5],[6] and references therein).

Precious clues on the pulsar physics were obtained from the e^+ measurements, but the large uncertainties in the data obviated any definitive statement. The PAMELA experiment observations on the $e^+/(e^+ + e^-)$ ratio [7] made a major contribution to solve this problem. PAMELA has been gathering data since June 2006 at solar minimum during a negative polarity ($A<0$) period with an unprecedented precision. Negative polarity epochs represent optimum periods to study any possible excess of cosmic-ray positrons with respect to the secondary component. In fact, under these conditions the global solar magnetic field affects positive particle fluxes more than negative ones (see for example [8] and references therein). Preliminary PAMELA measurements on the $e^+/(e^+ + e^-)$ ratio below 10 GeV [9] seem to confirm that the Moskalenko and Strong ([10]; hereafter M&S) calculations reproduce the observations fairly well when the whole effect of solar modulation, including drift, is taken into account. Therefore, no extra positron components need to be claimed below 10 GeV. In particular, no features are found near 6 GeV beyond a change of slope in the trend of the data [11]. Conversely, an increase of the positron fraction above 10 GeV with respect to the secondary component is confirmed by PAMELA. This experiment results are in good agreement, within errors, with the average trend of the best data sets published in the past up to 50 GeV where old data were available. Therefore the conclusions taken in [6] remain valid. Despite of that, the last two PAMELA data point trend seem to indicate an additional positron component above 50 GeV. We point out that preliminary results of this same experiment obtained with a better statistics and improved data analysis techniques indicate data points above 30 GeV approximately 15% lower [12]. However, since these updated data are not published yet and, for the moment, remain above our prediction, we will focus on the results reported in the Nature paper. We compare the possible third positron component with some plausible scenarios.

II. COSMIC-RAY POSITRON OBSERVATIONS AND PAIR PRODUCTION AT THE PULSAR POLAR CAP

Pulsed γ-ray flux observations from young pulsars such as Crab and Vela suggest that electromagnetic showers are produced in the pulsar magnetosphere [13]. Polar cap and outer gap models were proposed to explain this evidence (see for example [3]; [14]). The MAGIC [15] and Fermi LAT [16] experiments will clarify the role of these two processes in young and middle age pulsars. A recent study of $e^+/(e^+ + e^-)$ ratio versus energy [6] shows that the positron fraction measurements are compatible with a secondary origin of positrons [10] when solar modulation, including drift of opposite charge particles in the heliosphere, is considered, and an additional component of electrons and positrons from pulsar magnetosphere is added above a few GeV. In Fig. 1 the thick solid line indicates our prediction for the PAMELA experiment observations (solid stars) assuming a modulation parameter of 450 MV/c (preliminary results were reported in [17]). The dot-dashed curve represents the data trend expected during a positive polarity ($A>0$) epoch under the same modulation condition without the additional e^+ and e^- components from pulsars. PAMELA confirms our expectations below 10 GeV (region between dashed lines) and indicates this energy as the lower limit for a positron excess with respect to the secondary component. The most accurate data sets published before PAMELA (best fit and errors thin continuous lines in Fig. 1) show that the e^+ and e^-

extra components to be added to the secondaries above 10 GeV are found to be consistent with the model of pair production at the polar cap of young pulsars by Harding and Ramaty [3] when a normalization factor of 0.9 is applied to both particle fluxes [18]. However, it was pointed out that mature pulsars are favoured over young ones in producing electrons and positrons reaching the ISM, since a large part of them lies outside host Remnants ([6]; [14] and references therein). Average mature pulsar magnetic fields of a few $\times$ $10^{12}G$ and periods ranging between 200 and 300 ms allow us to reproduce the trend of the observed positron fraction above a few GeV by properly scaling the results reported in [3] (preliminary results appear in [5]). These parameters are found to be consistent with both average radio and gamma-ray pulsar observations [19]. In Fig. 1 our model prediction is confirmed up to 50 GeV by PAMELA.

While an acceptable agreement within experimental and model errors [6] can be claimed above this energy as well (more if 15% lower data points are considered), PAMELA might indicate an additional component of positrons above 50 GeV. Büshing et al. [20] and Hooper, Blasi and Serpico [21] have suggested that nearby pulsars such as Geminga and B0656+14 contribute most to positron fluxes observed near Earth at these energies. The characteristics of these pulsars are close to our estimates and it is plausible that close pulsars contribute more than far ones above a few tens of GeV. Gao, Jiang and Zhang [4] have shown that outer gap models are compatible with recent e^{+} and e^{-} observations as well. On the other hand, other possible nearby astrophysical sources might be responsible for the positron excess above 50 GeV [22] and a signature of supersymmetric particle annihilation cannot be excluded (see for example [23]).

III. Extra e^{+} components in addition to pulsar origin?

In Fig. 2 we report the expected positron flux to be observed by PAMELA in the case our estimate of the pulsar e^{+} and e^{-} components is considered in addition to secondaries (thick solid line). The solid stars represent the PAMELA data inferred from this experiment positron fraction measurements when the secondary calculations by M&S (dot-dashed line) and an equal flux of electrons and positrons is added (as it would be in case of a dominant component of pair produced in the pulsar magnetosphere). Obviously, the PAMELA expected data indicate the same sudden change of slope observed in the positron fraction observations. Please note as the MASS2 [1] and expected PAMELA data show an analogous trend near 10 GeV. Assuming no proton or electron contamination in the PAMELA positron sample above 50 GeV, it is possible to determine the characteristics of the positron component to be added to secondaries and pair produced in the magnetosphere of the galactic pulsar sample.

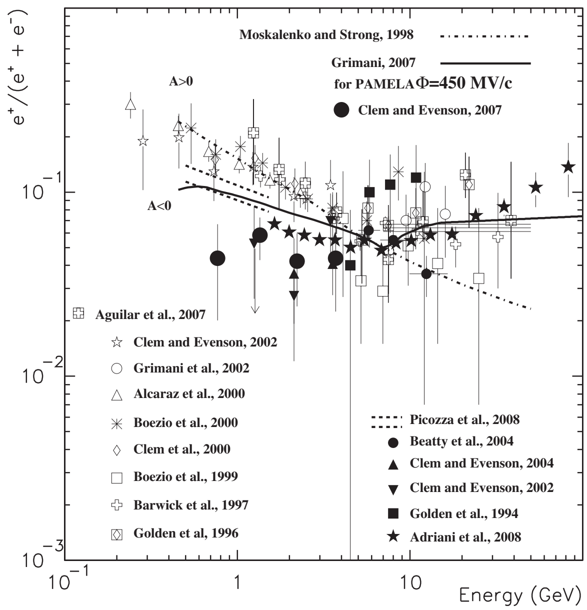

Fig. 1. Positron flux measurements (references to data are reported in [6]). The thin continuous lines indicate the average value (0.064±0.003) of the most accurate data sets published before PAMELA [1].

This "extra" positron component (thick dot-dashed line in Fig. 2) appears as it follows:

1) It matches the secondary component near 30 GeV.
2) Above 50 GeV is larger than the sum of the secondary and galactic pulsar components.
3) A feature similar to that at 10 GeV might be present at 30 GeV, typical of a new dominant power-law positron flux component.

The pulsar (nearby+galactic) contribution to e^{+} interstellar flux estimated by Hooper, Blasi and Serpico (dashed line in Fig. 2) matches very closely that found by Zhang and Cheng [14]. Consequently, both results are close to the PAMELA data points above 50 GeV. The additional e^{+} component with respect to secondaries and that generated in the galactic pulsar magnetosphere estimated by Hooper, Blasi and Serpico is represented by the dotted line in Fig. 2. The extra component indicated by PAMELA appears harder. Blasi [24] has recently determined the range of environmental parameter values in case e^{+} and e^{-} would be essentially generated in hadronic interactions inside the sources (indicated as old supernova remnants) where acceleration occurs. This scenario can be validated only by future observations of an increasing positron-to-electron and antiproton-to-proton fractions versus energy.

IV. The role of circumpulsar disks formed by supernova-fallback material

In a previous work ([25] and references therein) we have shown that positron observations in cosmic rays, the upper limit on gravitational wave energy losses from young pulsars due to pulsar ellipticities and friction

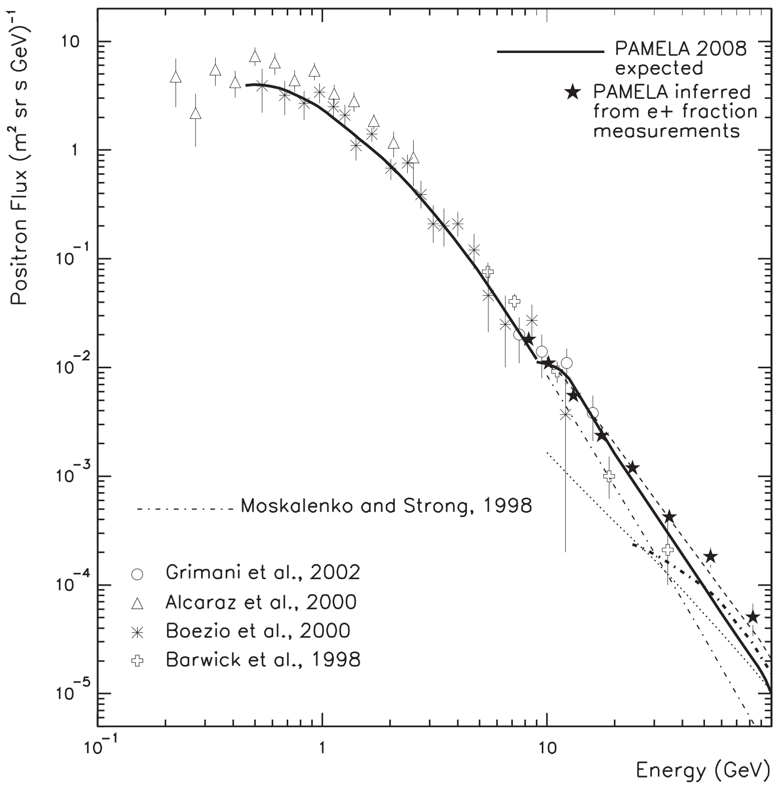

Fig. 2. Positron flux measurements. References to data appear in [18]. Details are reported in the text.

or propeller torque from circumpulsar disks lead to scenarios consistent with observed pulsar spin-down.

In particular, we have considered the role of supernova-fallback disks. We recall that the first observed planetary system different from ours belonged to a pulsar [26]. It is assumed that the planetary system formed from a debris disk. A disk was observed around the pulsar 4U 0142+61 as well [27]. Internal radii of disks surrounding young pulsars might have minimum size of 2000 km. Maximum disk mass at this same stage of a pulsar life can be reasonably assumed 10^{28} g (see [25] and references therein). The supernova-fallback mass rate for Crab was estimated by Menou, Perna and Hernquist [28] and found equal to 3×10^{16}-10^{17} g/s.

We have suggested that the presence of planetary systems and circumpulsar disks in a large sample of galactic pulsars might be studied through the detection of gravitational waves emitted by these systems with future space interferometers such as LISA (Laser Interferometer Space Antenna).

In this work we aim to determine the energy spectra of e^+ and e^- produced in the pulsar magnetosphere including the products of interactions of these particles in the circumpulsar supernova-fallback material.

Results will be presented at the conference.

V. Conclusions

The PAMELA $e^+/(e^++e^-)$ data confirm, on average, the trend of the most accurate data sets published in the past. Positrons result to be of pure secondary origin below 10 GeV. Between 10 GeV and 50 GeV pair production in the magnetosphere of the galactic pulsar sample appears to be one of the most plausible sources of cosmic-ray positrons in addition to secondaries. While the pulsar origin might dominate above 50 GeV as well, some extra positron component might overcome the other two at these same energies on the basis of the PAMELA highest energy data point trend. At the conference we will discuss the role of pair production in the circumpulsar supernova-fallback material.

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