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Cosmic-ray positron measurements: on the origin of the e$^+$ excess and limits on magnetar birthrate

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Catia Grimani[*]
University of Urbino "Carlo Bo", Urbino, INFN-Firenze, Italy
E-mail: catia.grimani@uniurb.it

Fifty years after the discovery of antimatter in cosmic rays at the top of the atmosphere, the trend of the most accurate measurements of positrons indicate an excess of these particles above 7 GeV with respect to the secondary component produced by primary cosmic rays propagating in the interstellar medium. This excess is studied here within the scenario of the last 25-year magnetic spectrometer observations. The characteristics of sources contributing to the overall e$^+$ flux observed near Earth as a function of particle energy are discussed. Pulsars and magnetars are considered plausible sources of cosmic-ray leptons. The consistency of this possibility is evaluated on the basis of inferred e$^+$ source characteristics and parameters set in several other astrophysics fields for these neutron stars. In case all pulsars and magnetars in the vicinity of Earth contribute to e$^+$-e$^-$ fluxes as expected, a larger positron excess would have been observed. Disks around pulsars and magnetars may play a role in quenching pair production in the magnetosphere of these neutron stars. The magnetar birthrate may also be overestimated.

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[*] Speaker.

1. Introduction

Antimatter in form of positrons was observed in cosmic rays at the top of the atmosphere for the first time in 1964 [1]. In 1979 two teams of american and russian scientists discovered antiprotons [2, 3]. While both observations were expected since e^+ and $\bar{p}$ are produced in primary cosmic-ray interactions in the interstellar medium, these old-time measurements indicated an excess of antimatter with respect to predictions based on a secondary origin only. A large number of experiments were devoted to antimatter hunting in cosmic rays since those days. Antiprotons are able to travel large distances in the interstellar and intergalactic media while positron and electron energy losses due to synchrotron radiation and inverse Compton scattering limit the distance of e^+ sources from Earth. In order to explain the excess of positrons both at low and high energies on the basis of the data available up to the end of the '90s, many hypotheses were considered in the literature: dark matter particle annihilation, evaporation by primardial black holes, pair production in the pulsar magnetosphere, e^+ from radioactive decay of ^{56}Co in young supernova remnants (see [4] and references therein). Single sets of observations, for instance, were used to claim for evidence of dark matter contribution to positrons in cosmic rays. The measurements carried out with several flights of the HEAT experiment, in particular, showed the presence of a feature in the positron excess between 7 and 10 GeV. What the HEAT observations actually revealed was a change of slope in the trend of the positron fraction data. This was suggested in [4] and confirmed by the PAMELA [5] and AMS [6] experiments. Conversely, the possible feature of the MASS2 observations at about 10 GeV was just a statistical fluctuation of the data [7].

Recent measurements that benefit of improved detector performance and data analysis techniques confirm the excess of positrons only above 7 GeV while the low-energy observations appear modulated by the solar activity intensity and drift process in the inner heliosphere.

Antiproton measurements carried out by the PAMELA experiment up to 200 GeV do not show any excess of antiparticles with respect to the secondary component [8]. The preliminary antiproton-to-proton ratio observations presented by the AMS collaboration up to nearly 500 GeV appear in excess with respect to the secondary component estimates at high energies. This trend, if confirmed by the absolute flux observations, will open new scenarios.

The characteristics of e^+ sources following from observational evidences are considered here. An astrophysical origin for cosmic-ray positrons remains, to our opinion, the most plausible possibility. In particular, we focus on e^+ pulsar and magnetar origin. The role of supernova fallback matter in forming disks around pulsars and magnetars affecting pair production in these neutron star magnetosphere is considered. The pulsar and magnetar birthrate are discussed critically.

2. Fifty years of cosmic-ray positron measurements

In figure 1 we have reported the cosmic-ray $e^+/(e^++e^-)$ ratio and positron flux measurements carried out during the last twenty years with magnetic spectrometer experiments (except for the Fermi-LAT data; Ackermann et al.; 2012) presenting a rejection power against protons better than 10^{-5}. Low-energy data appear modulated by the solar activity and drift in the heliosphere, while above a few GeV all experiments consistently indicate an excess of e^+ with respect to the estimated secondary component [9]. The experiments PAMELA and AMS have recently extended positron observations up to hundreds of GeV. It is worthwhile to point out that, despite the large statistical errors affecting the measurements of old experiments, the average value of the $e^+/(e^+ + e^-)$ ratio (region between the three solid lines in the left panel of figure 1) appears consistent with the average trend of the PAMELA and AMS data between 7 GeV and 50 GeV.

The positron flux measurements carried out by the AMS experiment between 20 GeV and 500 GeV [12] were fitted here with a power-law function:

$$F(E) = 7.61 \times E^{-2.77^{+0.11}_{-0.03}}\ Particles/(m^2\ sr\ s\ GeV). \tag{2.1}$$

Maximum fitting errors have been considered in our work in order to include possible substructures in the e^+ flux. When the positron secondary component is assumed equal to (dot-dashed line in the right panel of figure 1; [9]):

$$F(E) = 34.71 \times E^{-3.55}\ Particles/(m^2\ sr\ s\ GeV), \tag{2.2}$$

in the same energy range, the excess of positrons with respect to this secondary component can be expressed as it follows (dotted line in the right panel of figure 1):

$$F(E) = 0.82 \times E^{-2.44}\ Particles/(m^2\ sr\ s\ GeV). \tag{2.3}$$

We find that the diffuse spectrum of electrons measured by the AMS collaboration [12] is consistent with a power-law function with a spectral index of 3.23±0.10 above 20 GeV. The difference between this spectral index and that of the overall e^+ flux is 0.46±0.12, while the spectral index of the positron extra component differs by 0.79 from that of the electron flux. Our results agree with those reported by the AMS collaboration within errors.

3. On positron source characteristics

Starting from the observational scenario on positrons and electrons described above, we consider the characteristics of possible sources of e^+ in the Earth nearby interstellar medium. In [13] we showed that the PAMELA positron data up to 100 GeV are consistent with only one source of positrons located within 250 pc from Earth by assuming the following energy input spectrum:

$$F(E) = 2.6 \times E^{-2.01} \tag{3.1}$$

and a simple Green's function solution to the general non-stationary diffusion equation obtained by considering e^+ radiative energy losses (see [14] and references therein) in the interstellar medium.

Middle aged pulsars and magnetars are plausible sources of e^+ and e^-: the magnetosphere of these neutron stars are obvious reservoirs of leptons, even though the acceleration and confinement processes in the nebulae surrounding the pulsars, for instance, remain to be fully understood. Recently, the contribution of millisecond pulsars was also estimated in [15].

4. Pulsar and magnetar birthrate and spatial distribution

The actual number of middle aged pulsars and magnetars in the Solar System vicinity can be estimated on the basis of these neutron star birthrates and their spatial distribution in the galactic

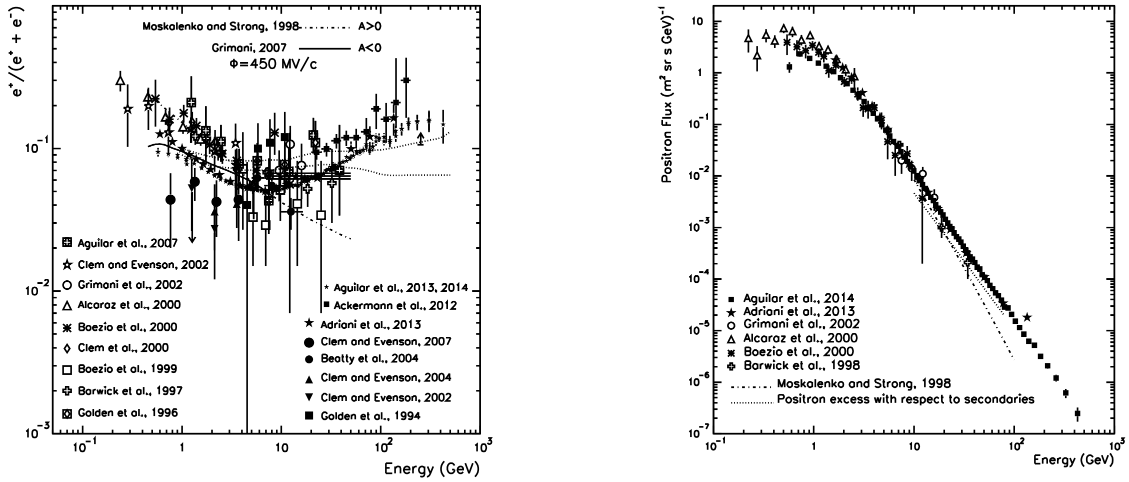

Figure 1: Left panel: positron fraction measurements in cosmic rays gathered during positive polarity periods (A> 0; open symbols) and negative polarity periods (A< 0; solid symbols). The dot-dashed line indicates the estimated trend of the $e^+/(e^+ + e^-)$ ratio [9] at solar minimum during positive polarity epochs when only the secondary e^+ component is considered. The thick continuous line represents an empirical estimate of the positron fraction during negative polarity periods for a medium-low level of solar activity. The three continuous lines indicate the average positron fraction measurements between 7 GeV and 50 GeV with errors [10] before the publication of the data gathered by the PAMELA [5] and AMS experiments [6]. The dotted lines represent the expected magnetar contribution (see [11] for details). Right panel: positron flux measurements in cosmic rays gathered during positive (A> 0; open symbols) and negative polarity periods (A< 0; solid symbols). The dot-dashed line indicates the estimated trend of the secondary positron component [9]. The dotted line represents the excess of e^+ with respect to the secondary component.

disk. Isolated neutron stars are supposed to be genetically connected to supernova events. Therefore, the supernova explosion rate in the Galaxy of one every 50 years approximately sets an upper limit to the pulsar birthrate. Analogously, the space distribution of massive, short lived stars in the Galaxy spiral arms constrains the pulsar distribution. Estimates of pulsar birthrate are usually carried out on the basis of radio surveys of isolated, rotation-powered, radio emitting pulsars. We recall that only a small number of neutron stars in the Galaxy are visible to Earth-bound experiments as radio pulsars. Arzoumanian, Chernoff and Cordes [16] studied the velocity distribution of isolated radio pulsars using large-scale 0.4 GHz pulsar surveys. In their work, they pointed out that Soft Gamma Repeaters (SGRs), Anomalous X-Ray Pulsars (AXPs), pulsars in binary systems and radio-quiet pulsars were not taken into account. Therefore, their findings of one pulsar born every 760 years underestimate the actual pulsar birthrate. In [17] this parameter was also determined on the basis of a Parkes multibeam survey. Other observations from previous radio surveys appear in the same paper and are displayed in figure 2.

Attempts to set a limit to the pulsar birthrate using low-uncertainty measurements of the $e^+/(e^+ + e^-)$ ratio and absolute electron energy differential flux observations in cosmic rays were carried out in [13] and references therein. In [20] we found that the upper limit to the uncertainty on the pulsar birthrate set in [13] of one pulsar born every 33 years is of 30%. Therefore, the most recent and accurate measurements of positrons in cosmic rays indicate a pulsar birthrate ranging between 23 and 43 years (see GR11 in figure 2). Analogous findings would have been obtained with the AMS data superposing well the PAMELA observations up to 100 GeV. We recall that 50 GeV represent the upper limit to the energy of e^+ possibly generated by the bulk of galactic pulsars while above this energy, the contribution of nearby pulsars should overcome that of the overall galactic sample. In [21], for instance, Hooper, Blasi and Serpico considered the role of near-Earth pulsars in contributing to positron observations in cosmic rays up to 100 GeV. These authors find a birthrate of one pulsar born every 25 years, consistently with our result. In conclusion, the hypothesis of a positron origin from pulsars leads to an estimate of the pulsar birthrate consistent with radio observations. Rounding the average value of data reported in figure 2, it is reasonable to assume a pulsar birthrate in the Galaxy of one pulsar born every 60 years. This finding appears in excellent agreement with the recent result of one pulsar born every 59 years following from a Monte Carlo simulation normalized to the Fermi-LAT observations of young γ-ray pulsars (WR11 in figure 2; [19]).

The pulsar spatial distribution was studied in [18] and [22], among others. In particular, Faucher-Giguère and Kaspi [18] show that pulsars are concentrated in the Milky Way spiral arms and present a radial distribution of these neutron stars with a maximum at 3.5 kpc from the galactic center (GC). Similar results are obtained by Guseinov and Kosumov [22]. On the basis of figure 2 in both papers, we estimate that approximately 13% of galactic pulsars are found in the region between 7.5 kpc and 9.5 kpc from the GC. This fraction increases to 36% between 6 kpc and 11 kpc. We recall that the Solar System lies at 8.5 kpc from the GC.

The pulsar birthrate reported above and the upper limit to the active pulsar lifetime, reasonably set here at 2×10^7 years, allow us to find that the maximum number of active pulsars in our galactic disk is 3.3×10^5. This simple estimate is consistent with the results obtained with radio surveys (see [20] and references therein).

Middle aged pulsars up to 5×10^5 years are expected to contribute predominantly to positron observations near Earth ([10] and references therein). By assuming a uniform distribution of active pulsars versus age, a fraction of 2.5% of the galactic sample is constituted by pulsars younger than 5×10^5 years: this amounts to 8250 pulsars.

The average number density of young and middle aged pulsars within 1 kpc from the solar system results to be 33 pulsars kpc^{-3}. This finding follows from the work by Faucher-Giguère and Kaspi [18] and Guseinov and Kosumov [22] by considering an effective Milky Way disk volume of 32.8 kpc^3 for the region between 7.5 and 9.5 kpc from the GC by assuming an average thickness of the galactic disk of 300 pc. The volume of the Galaxy within 1 kpc from Earth is, therefore, 0.96 kpc^3. The number of active pulsars within 1 kpc from Earth thus estimated is 32. These pulsars may contribute to e^+-e^- fluxes observed near Earth up to hundreds of GeV. The number of pulsars being possible e^+ sources within 250 pc from the solar system would be 2 consequently. Pulsars like Geminga and B0656+14 are plausible candidates even if a disk around B0656+14 may quench the particle production in the magnetosphere of this neutron star [23].

Magnetars are isolated neutron stars characterized by surface magnetic fields of 10^{14}-10^{15} G and internal fields $>10^{15}$ G. They are supposed to emit persistent X-ray fluxes pulsed at a few seconds with typical luminosity of 10^{35}-10^{36} erg/s at energies of $\simeq$ 1 keV - 200 keV. The emission is due to neutron star spindown. Magnetars may also produce short bursts of soft gamma rays of durations 0.1-1 s (luminosity of $\simeq 10^{39}$-10^{42} erg/s) or giant flares with luminosities $>10^{44}$ erg/s (more rare). These energetic events are supposed to be due to giant crustal fractures. Because of the high magnetar magnetic fields, the period derivatives of these neutron stars range between 10^{-9} and 10^{-11} s s^{-1}, while in regular pulsars these values are of the order of 10^{-12}-10^{-13} s s^{-1}. Magnetars are supposed to have periods smaller than 3 ms at birth. Different estimates are found in the literature about magnetar birthrate. Gill and Heyl [24] find a birthrate of one magnetar born every 545.6 years. Muno et al. [25] estimate that the same parameter ranges between 0.3 and 6 magnetars born per century. Basically, magnetars are expected to be 10% or more of the pulsar sample. These neutron stars were proposed to be the main contributors to the positron excess in cosmic rays below 100 GeV [11]. It is worthwhile to point out that these predictions appear higher than present observations in an energy range where the solar modulation does not affect e^+ measurements. In case the magnetar birthrate would result overestimated, their contribution to cosmic rays should be reconsidered accordingly. At present time, it can be reasonably assumed that at least 3 magnetars may contribute to positron observations in the Earth vicinity in addition to 32 pulsars. In other words, there are several possible sources of positrons and electrons within a few hundreds of pc from the solar system. In order to evaluate the actual contribution of each pulsar and magnetar, the role of disk formation around these neutron stars should be properly taken into account.

5. Disks around pulsars and magnetars and magnetar birthrate

In [26] it was shown that fallback disk formation near the light cylinder of pulsars is allowed in case pulsar initial periods are larger than tens of milliseconds. Circumpulsar disk formation and detection through gravitational wave emission generated by disks undergoing precession was discussed in [20]. In [27] we showed that circumpulsar disk formation in the pulsar magnetosphere is compatible with positron average observations near Earth. However, disk partially or totally quenching particle production may limit the contribution of individual pulsars to e^+ observations near Earth as it was suggested for B0656+14 in [23]. Geminga remains the most plausible source of positrons observed in cosmic rays in addition to the secondary component at high energies. The formation of disks around pulsars was also claimed in the literature to explain observations from SGRs and AXPs. In [28] it was pointed out that part of new-born magnetars may become black holes due to matter accretion on the star and therefore, the estimate of the magnetar birthrate reported above should be considered an upper limit. From the $e^+/(e^++e^-)$ estimates reported in the left panel of figure 1 as dotted lines, we may conclude that the magnetar birthrate should be smaller than a factor of two with respect to the mentioned estimates.

6. Conclusions

Positron observations are found compatible with the hypothesis that pulsars and magnetars in the Earth vicinity contribute to e^+-e^- fluxes in the case the magnetar birthrate, estimated to be about 10% of that of pulsars would result more than a factor of two smaller. Another possibility is that partial or total quenching of pair production in the pulsar and magnetar magnetosphere due to circumpulsar disk formation reduce the number of neutron stars that contribute to the overall flux

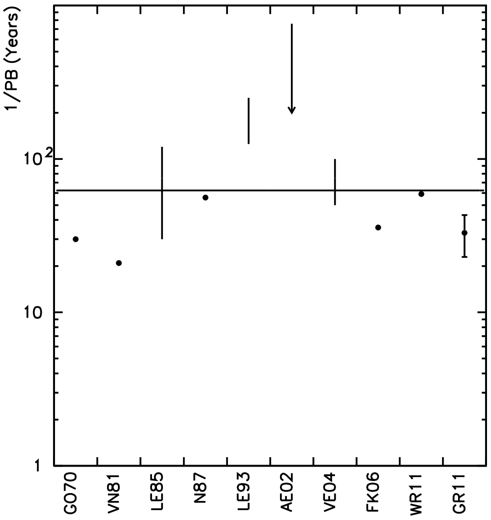

Figure 2: Pulsar birthrate estimates obtained with radio surveys ([17]), [18] and references therein), pulsed gamma-ray observations (WR11 [19]) and e$^+$ cosmic-ray observations (GR11; [13]). The solid horizontal line represents the average pulsar birthrate of one pulsar born every 62 years estimated on the basis of the data reported in the figure.

of positrons near Earth. Multimessenger investigations are needed to detect the formation of disks around a large sample of pulsars and magnetars.

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