Antimatter origin and average pulsar parameters from e^+ measurements

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***Abstract*— Recent $e^+/(e^+{+}e^-)$ measurements allow us to set an upper limit to the positron flux excess in cosmic rays with respect to the secondary component above a few GeV. This flux excess is compatible with a model of pair production at the pulsar polar cap. On the basis of this scenario, we have determined the average parameters of galactic radio pulsars contributing to e^+ and e^- interstellar fluxes. A good agreement is found with present observations of both radio and gamma-ray pulsars. Future results of the PAMELA and GLAST experiments will allow us to support or to reject these speculations.**

I. Introduction

Positrons and antiprotons were detected in cosmic rays for the first time in 1964 [1] and 1979 [2], [3], respectively. Early time observations seemed to show a major excess of antimatter with respect to the estimated secondary component, produced by primary cosmic-ray collisions in the interstellar medium. Probably due to the improvement of particle detectors and data analysis techniques, e^+ and $\overline{p}$ measurements carried out during these last ten years present lower values compared to the past (see for example [4]-[6]).

In particular, recent positron measurements above a few GeV are compatible with a minor, if any, excess of positrons with respect to the band of uncertainty of the secondary component calculations ([7] and references therein). The attempt to use low energy data to discriminate among various secondary e^+ flux calculations is affected by opposite clues given by different experiments about the role of the solar modulation on positive and negative charge particles. Consequently, presently available data allow us to set only an upper limit to the positron flux excess with respect to the secondary component above a few GeV (see [8] for details). This upper limit presents the same trend of a model of e^+e^- pair production at the pulsar polar cap of young pulsars [9]. However, it has pointed out that middle aged pulsars are favoured over young ones in producing electrons and positrons reaching the interstellar medium [10], [11]. According to this last hypothesis, we determine the average parameters of the galactic pulsar sample giving a contribution to the e^+ interstellar flux with the use of recent $e^+/(e^+{+}e^-)$ measurements.

II. Comparison of secondary positron and electron flux calculations to observations

It has been shown that only experiments carried out during these last ten years present rejection factors of e^+ against

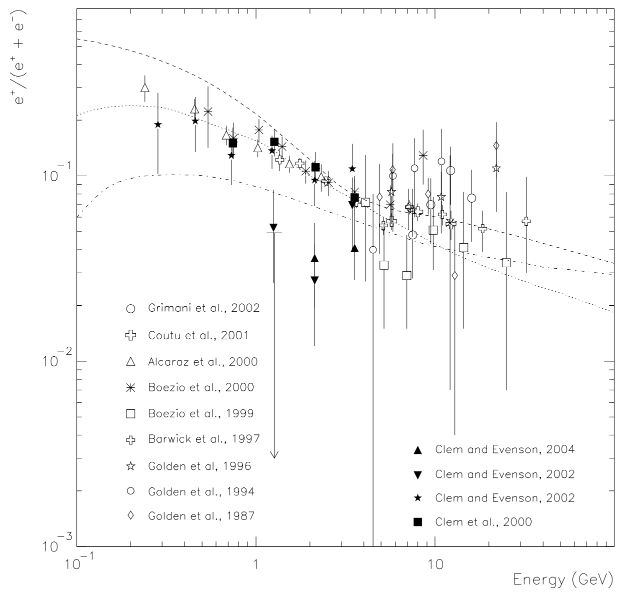

Fig. 1. Positron observations published during the last ten years. Data are compared to theoretical calculations by Protheroe [21] (dot-dashed line), Moskalenko and Strong [22] (dotted line) and Stephens [23], [24] (dashed line).

protons to be considered reliable for positron observations in spite of the large statistical uncertainties ([7] and references therein). These measurements are reported in Fig. 1 [4], [12]-[20]. No major excess of positrons with respect to the band of uncertainty of the expected secondary component [21]-[24] is observed. It is important to emphasize that among various $e^+/(e^+{+}e^-)$ calculations there is almost one order of magnitude difference at a few hundreds of MeV and approximately a factor of two above a few GeV. When data below a few GeV are compared to theoretical models, the different modulation of the Sun on positive and negative particles during opposite polarity periods must be taken into account.

The LEE and AESOP experiment data reported in Fig. 2 are in agreement with the calculations by Protheroe based on a Simple Leaky Box Model when positron and electron fluxes are properly modulated during a positive (A>0) or negative

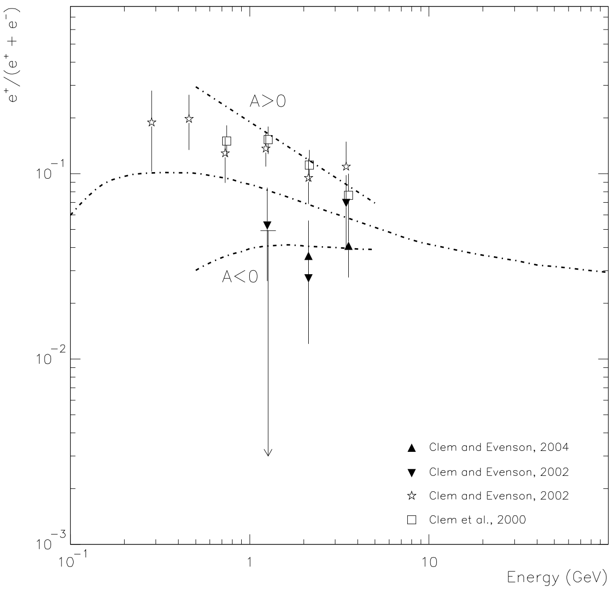

Fig. 2. LEE and AESOP experiment data gathered during positive (A>0; open symbols) and negative (A<0 solid symbols) solar polarity epochs. The central line represents the Simple Leaky Box Model calculation by Protheroe at the interstellar medium [21]. Top and bottom curves correspond to the same model properly modulated by the effect of the Sun during different polarity periods ([20] and references therein).

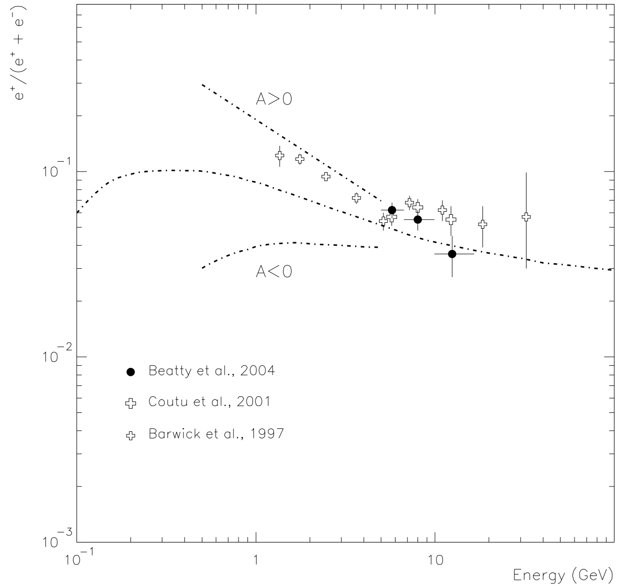

Fig. 3. HEAT experiment data. Open, solid symbols and curves have the same meaning than in fig. 2.

(A<0) polarity epoch ([18]-[20]). The HEAT experiment results in Fig. 3 [25], [12], [16] do not present this evidence and agree better with the Stephens calculations (Fig. 1).

In Fig. 4 [4], [13], [14], [28], [29],[27], [30] the comparison of the electron fluxes estimated at the interstellar medium indicates that there is a convincing agreement among the Ferreira et al. [26], Moskalenko and Strong and Protheroe calculations while the Stephens calculations are lower mainly below a few GeV. The calculation by Ferreira et al., when propagated near Earth during a negative polarity epoch, is in exceptional agreement with the data by Evenson et al. [27] (large diamonds). On the other hand, the calculations by Stephens modulated near Earth assuming a modulation parameter (ϕ) of 550 and 1200 MV/c (thin dot-dashed and dotted lines, respectively, in Fig. 4) show the same trend of the Boezio et al. [14], and Evenson et al. (small diamonds in Fig. 4 [27]) data. Radio observations [31] show a slightly better agreement with the Stephens calculations. The PAMELA experiment [33] (launched on June 15th 2006) is supposed to take data for the next three years during a negative polarity epoch in the energy range 50 MeV - 270 GeV with an imprecedented precision. PAMELA is expected to allow us to discriminate among various theoretical models in the very near future.

At this time we can only set an upper limit to the positron flux excess with respect to the secondary component above a few GeV. To this purpose, we chose to use the calculations by Moskalenko and Strong [22] at the lower edge of the band

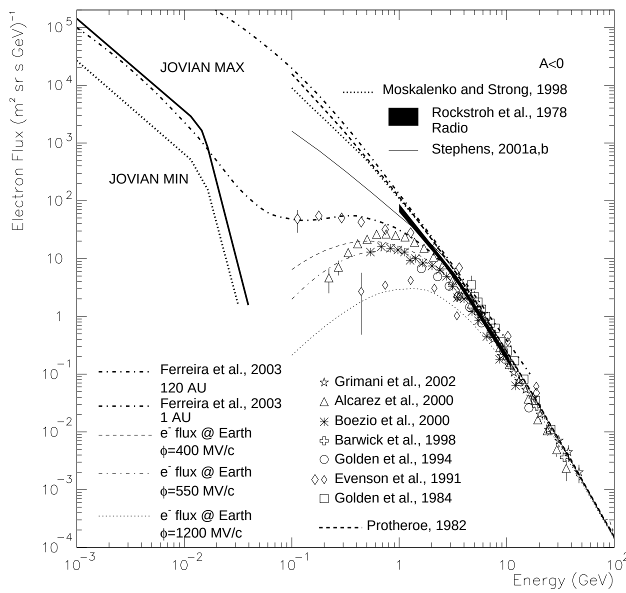

Fig. 4. Interstellar (top thick dot-dashed line [26]; thick dashed line [21]; thick dotted line [22]; continuous line [23],[24]), interplanetary (bottom thick dot-dashed line [26] during a negative polarity epoch) and primary near Earth (dashed line - modulation parameter ϕ=400 MV/c; dot-dashed line - ϕ=550 MV/c; dotted line - ϕ=1200 MV/c [23],[24]) electron flux calculations. Minimum (thick dotted line) and maximum (thick continuous line) contribution of jovian electron flux is indicated [32]. Symbols represent electron flux measurements at 1 AU.

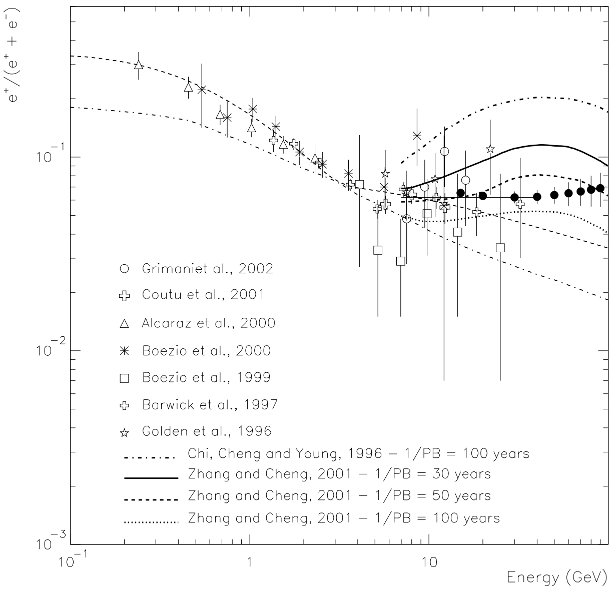

Fig. 5. Comparison of positron fraction observations to theoretical models of electron-positron pair production in the pulsar magnetosphere. The top thick dot-dashed line indicates the Chi, Cheng and Young model [10] assuming a mixed polar cap and outer gap pair production (thick dot-dashed line). Zhang and Cheng consider an outer gap model with different pulsar birthrate values [11](thick solid, thick dashed and thick dotted lines). The continuous thin line indicates the best-fit to the data above 7 GeV. Solid dots represent the expected PAMELA observations in case of a polar cap contribution to the electron and positron fluxes.

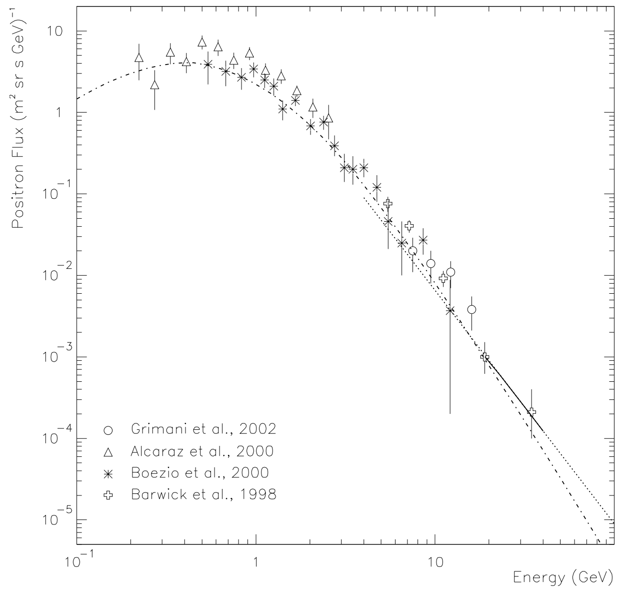

Fig. 6. Near Earth positron flux observations (symbols) and calculations (dot-dashed line - secondary e^+ component [22]; dotted line e^+ calculated in [9] on the basis of a polar cap model of positron production at the pulsar polar cap with a normalization factor of 0.9). The continuous thick line represents the upper limit to the e^+ flux in excess with respect to the secondary component above 20 GeV. See text for details.

of uncertainty of the secondary e^+ calculations and being based on a reasonable diffusion model (dotted curve in Fig. 1). We subtract the secondary e^+ and e^- flux calculations reported in [22] from the $e^+/(e^++e^-)$ data best fit represented by the constant value of 0.064 ± 0.003 above 7 GeV (thin continuous line in Fig. 5 [4]). The resulting upper limit to the e^+ flux excess is reported in Fig. 6 as a continuous thick line above 20 GeV. In the same figure we have reported the e^+ flux calculated by Harding and Ramaty [9] on the basis of a pair production model at the pulsar polar cap of young pulsars (thick dotted line) when a normalization factor of 0.9 is considered. The two curves superimpose perfectly. We have chosen to report the upper limit to the e^+ flux above 20 GeV, since, on the basis of the Harding & Ramaty work at this energy, the pulsar positron component overcomes the secondary one.

In [9] a pulsar lifetime for electron and positron production of 10^4 years, the pulsar parameters of Crab and Vela and a pulsar birthrate (PB) of one pulsar born every 30 years were considered. The 0.9 normalization factor implies an assumption of a pulsar birthrate of one pulsar born every 33.3 years. This result is in very good agreement with the very last observations of the Parkes multibeam survey [34] that finds 2.8 pulsar born per century (1/PB=35.7 years). We recall that the comparison of the set of recent, $e^+/(e^+ + e^-)$ available data above a few GeV with the whole region of uncertainty of the secondary component calculation leads to 1/PB equal to 200 ± 100 years [7]. To summarize, recent e^+ measurements are consistent with a positron secondary origin based on the diffusion model reported in [22] with an extra positron component produced at the pulsar polar cap of young pulsars. We are aware that other hypotheses can be considered for the e^+ origin (see for example [7]) and that criticisms can be made to the scenario proposed in this work. In the next section, we focus on some of these criticisms and determine the average pulsar parameters that lead to the same results reported in [9] considering a polar cap model for the whole galactic radio pulsar sample. We will also indicate what we expect for future experiment observations in case our speculations are correct.

III. Constraints on Pulsar Parameters from Positron Observations

It has been argued that e^+ and e^- produced in the magnetosphere of young pulsars do not escape the surrounding remnants [10]. Arzoumanian, Chernoff & Cordes [35] have estimated the fraction of pulsars outside host remnants versus age (Fig. 7). Mature pulsars are favoured over young ones in producing e^+ and e^- reaching the interstellar medium [11]. Harding has recently stressed that, in principle, polar cap models predict that all pulsars are capable to emit gamma rays to some extent [36]. It is worth to evaluate if the hypothesis of a large sample of pulsars with a small efficiency for pair

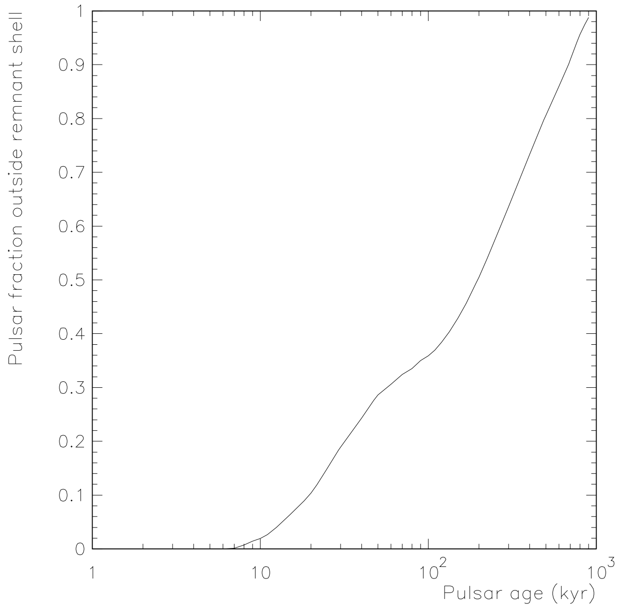

Fig. 7. Estimated fraction of pulsars outside host remnants as a function of their age [35].

production leads to a result similar to that reported in the Harding and Ramaty original work for young pulsars [9]. In [9] only 0.0625% of the galactic sample was considered if a pulsar average age of 16×10^6 years is reasonably assumed. In the same work an e^+ luminosity per pulsar proportional to B_{12} $P^{-1.7}$ (where B_{12} is the pulsar surface magnetic field in terms of 10^{12} Gauss and P is the period in seconds) was estimated. In order to take into account the whole sample of galactic pulsars, the average luminosity per pulsar should decrease by about two orders of magnitude with respect to that assumed by Harding and Ramaty. Therefore, the parameters of the Crab (B_{12}=3.8 P=0.033 s) and Vela (B_{12}=3.4 P=0.089 s) pulsars used in [9] should be changed accordingly. In Figs. 8 and 9 we have reported the observed characteristics of galactic radio pulsars. It can be noticed that the magnetic fields of the Crab (12.58) and Vela (12.53) pulsars lie near the peak of the distribution. Conversely, the observed pulsar period distribution peaks at about 0.5 s and therefore the values assumed in [9] appear at the very left edge of the distribution in Fig. 9. If the average radio pulsar magnetic field is similar to that used in [9], we conclude that the average period of radio pulsars contributing to e^+ and e^- fluxes in the interstellar medium should range between 200 and 300 ms. These values are closer to the peak of the observed distribution. Moreover, a period of 200-300 ms might indicate that the major contribution to interstellar electron and positron fluxes is given by pulsars maintaing a good efficiency for pair production (the youngest among those escaped from host remnants).

In Table I we have reported the characteristics of the observed gamma-ray pulsars. The average magnetic field is

TABLE I

OBSERVED GAMMA-RAY PULSAR CHARACTERISTICS

Pulsar	Age (years)	Magnetic field (10^{12} G)	Period (ms)
Crab	1300	3.8	33
B1509-58	1500	15.4	150
Vela	11000	3.4	89
B1706-44	17000	1.165	102
B1951+32	110000	1.1	40
Geminga	340000	1.6	237
B1055-52	530000	0.97	197

3.92×10^{12} G with a standard deviation of 4.81×10^{12} G while the average period is 121 ms with a standard deviation of 71 ms. The comparison is encouraging but not conclusive because of the large statistical uncertainties on the observed gamma-ray sample characteristics.

Low-error e^+ measurements and pulsed gamma-ray observations from a large sample of pulsars are needed in order to support or to reject the scenario for the e^+ origin proposed in this work. The results of the PAMELA experiment are expected to be compatible with those by GLAST. In particular, we expect for the PAMELA observations those reported in Fig. 5 as solid dots (upper limit). While the secondary e^+ component is supposed to show a decreasing trend as a function of the energy, an additional pair contribution from pulsar polar cap should give a flat trend to the $e^+/(e^++e^-)$ ratio above a few GeV. The positron fraction measurements should converge towards an asymptotic value of 0.5 in case the polar cap origin would become overwhelming with respect to the secondary one. The GLAST [38] experiment will show if outer gap electromagnetic energy losses in the magnetosphere of pulsars overcome those at the polar cap. Chi, Cheng and Young [10] and Zhang and Cheng [11] have calculated the $e^+/(e^++e^-)$ ratio on the basis of a mixed model of polar cap and outer gap pair production or a pure outer gap origin for electrons and positrons generated in the magnetosphere of pulsars, respectively. In Fig. 5 these models have been reported as thick dot-dashed, continuous, dashed and dotted lines, specifically.

IV. CONCLUSION

We have compared the $e^+/(e^++e^-)$ ratio data published during these last ten years to various sets of calculations. Low energy data are affected by different modulation on e^+ and e^- during opposite solar polarity epochs. Above a few GeV we have determined the upper limit to the positron flux in excess with respect to the band of uncertainty of the secondary component. We have assumed a model for e^+ and e^- production at the polar cap of radio pulsars. We have found that the average magnetic field and period for pulsar contributing to the e^+ and e^- interstellar fluxes must be a few times 10^{12} G and of 200-300 ms, respectively. These values are in good agreement with both radio and gamma-ray pulsar observations. Low-error positron and pulsed gamma-ray observations from a large sample of pulsars will allow us to confirm or to reject the hypotheses presented in this paper.

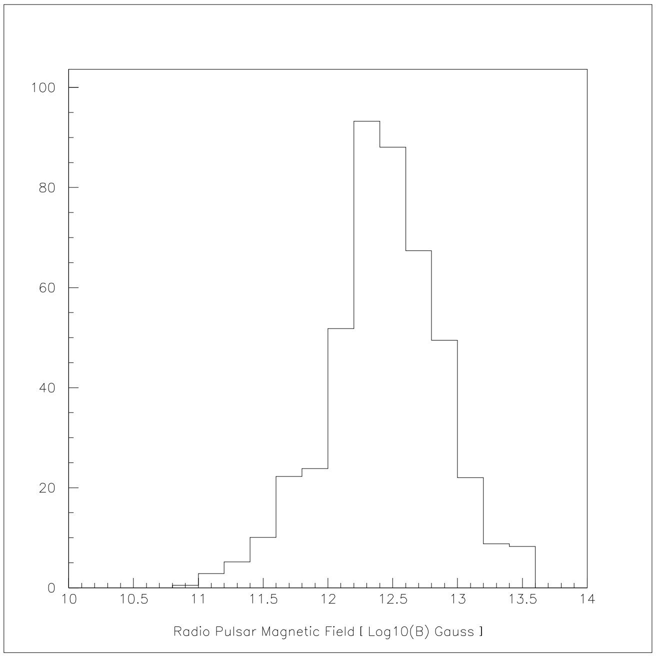

Fig. 8. Distribution of radio pulsar observed magnetic field [37].

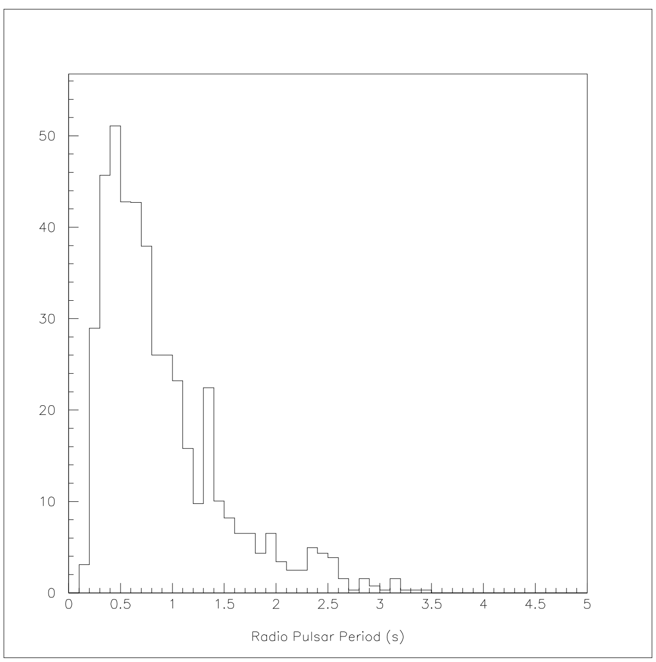

Fig. 9. Distributin of radio pulsar oberved period [37].

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