

Pulsar birthrate set by cosmic-ray positron observations

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Abstract. The pulsar birthrate (PB) in our galaxy is a parameter known with a large uncertainty. Different estimates indicate that $1/\text{PB}$ ranges between 30 and 250 years. Assuming a polar-cap model for gamma-ray production in gamma-ray pulsars, positron fraction measurements in cosmic rays above a few GeV make it possible to set a limit on PB. Recent measurements of the $e^+/(e^+ + e^-)$ ratio indicate a PB of one pulsar born every 200 ± 100 years when the uncertainty on the secondary positron calculations is taken into account. A PB compatible with this result is found even in the case of a relevant production of positrons in the pulsar outer gaps.

Key words. stars: pulsar: general – ISM: cosmic-rays

1. Introduction

Electrons and positrons were discovered in cosmic rays in 1961 (Meyer & Vogt 1961) and 1964 (De Shong et al. 1964), respectively. Electrons outnumber positrons by approximately one order of magnitude. For this reason it is believed that electrons are mainly of primary origin while positrons are expected to be produced by cosmic-ray interactions in the interstellar medium.

The study of e^- and e^+ energy spectra gives precious hints about cosmic-ray acceleration and propagation processes. As low mass particles (0.511 MeV), electrons and positrons undergo major energy losses through inverse Compton scattering and synchrotron radiation. The comparison of proton-nucleus energy spectra with those of electrons and positrons allows the determination of the transverse component of the magnetic field and the average photon energy density in the interstellar medium (see for example Golden et al. 1984).

Electrons and positrons are rare particles in cosmic rays ($e^+/p \simeq 10^{-3}$, $e^-/p \simeq 10^{-2}$, and therefore $e^+/e^- \simeq 10^{-1}$, at a few GeV). It was only with the use of magnetic spectrometers that it was possible to reliably determine their absolute energy differential fluxes and charge ratio, ($e^+/(e^+ + e^-)$) (Golden et al. 1987; Golden et al. 1994).

Measurements of the $e^+/(e^+ + e^-)$ ratio carried out until the middle 1990s seemed to show an important excess of positrons at energies larger than 10 GeV with respect to the secondary component (see for example Muller & Tang 1987). These observations were the source of many theoretical speculations about the processes that might have generated additional positrons.

Among such processes considered were: Primary Black Hole annihilation (PBH) (Carr 1976; Carr & MacGibbon 1998), radioactive decay of ^{56}Co in young supernova remnants

(Skibo & Ramaty 1993), galactic halo weakly interacting massive particle (WIMPs) annihilation (Turner & Wilczek 1990), $\gamma\gamma$ pair production from high energy gamma rays interacting with optical and ultraviolet radiation (Aharonian & Atoyan 1991), e^+ production in pulsar polar-cap electromagnetic cascades (Sturrock 1971; Daugherty & Harding 1982).

Data published in the last few years (Barwick et al. 1997; Boezio et al. 1999; Coutu et al. 2001) seem to indicate a milder excess of positrons (if any) with respect to the secondary component.

In this paper an overview is given of the positron measurements and theoretical calculations of e^+ generated in the interstellar medium published in the last two decades. For a possible extra source of positrons, e^+ production in the pulsar magnetosphere is considered and an improved limit (for a previous work see Grimani 1996) to the PB has been set on the basis of the most recent $e^+/(e^+ + e^-)$ ratio measurements.

2. Positron measurements and secondary interstellar calculations in the last two decades

Electron and positron detection in cosmic rays has been mainly accomplished in the past with instruments carried by stratospheric balloons at the top of the atmosphere. Magnetic spectrometers have been proven to be the most reliable detectors used for rare particle identification such as positrons and antiprotons (see for example Golden et al. 1994; Hof et al. 1996). However, instruments with small collecting power and with short exposure time, characteristic of balloon-borne experiments, have only allowed the study of positrons up to energies of a few tens of GeV and, in most cases, with a very small statistical sample. Only 9 measurements of the absolute flux of positrons are available in the literature (see Grimani et al. 2002 and references therein). The large statistical and normalization

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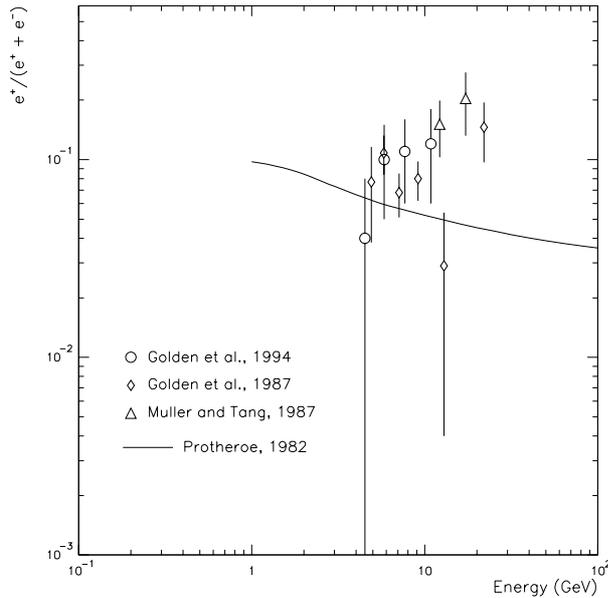


Fig. 1. Positron-to-electron relative ratio measurements carried out between 1985 and 1995. The data have been compared to the theoretical predictions of the LBM (continuous line – Protheroe 1982).

errors on absolute fluxes have indicated the $e^+/(e^+ + e^-)$ ratio as the best tool for positron study.

In Fig. 1, we report data published between 1985 and 1995. This period has been chosen to disregard the data obtained with very old instruments. In spite of the large statistical errors, an excess of positrons can be noticed above a few GeV with respect to the secondary component estimated on the basis of the Leaky Box Model (LBM) (Protheroe 1982).

The experimental scenario has changed in the last few years. In Fig. 2 the most recent $e^+/(e^+ + e^-)$ ratio measurements are reported (Grimani et al. 2002; Coutu et al. 2001; Alcaraz et al. 2000; Boezio et al. 2000; Boezio et al. 1999; Barwick et al. 1997; Golden et al. 1996).

These data, compared to the theoretical expectations of the LBM (thick solid line), might still show an excess of positrons with respect to the secondary component but not so important as it seemed to be in the past. In this respect, it has to be taken into account that two new sets of theoretical calculations are now available in the literature (Moskalenko & Strong 1998 (M&S); Stephens 2001a, 2001b). These calculations, reported for the interstellar medium and near the Earth, have been compared with those of Protheroe in Fig. 2. A modulation parameter of 0.55 GV/c was used in order to take into account the solar modulation effect near the Earth (details are reported in Grimani et al. 2002). No re-acceleration process and regular proton input spectra have been considered for the M&S calculations.

Below a few GeV the solar modulation plays an important role and therefore it is very hard to discriminate between different models. All computations seem to agree pretty well at 3–4 GeV.

Above 5 GeV, where the effect of solar modulation can be neglected, calculations differ by more than a factor of two. Only future, low error measurements at low and high energies

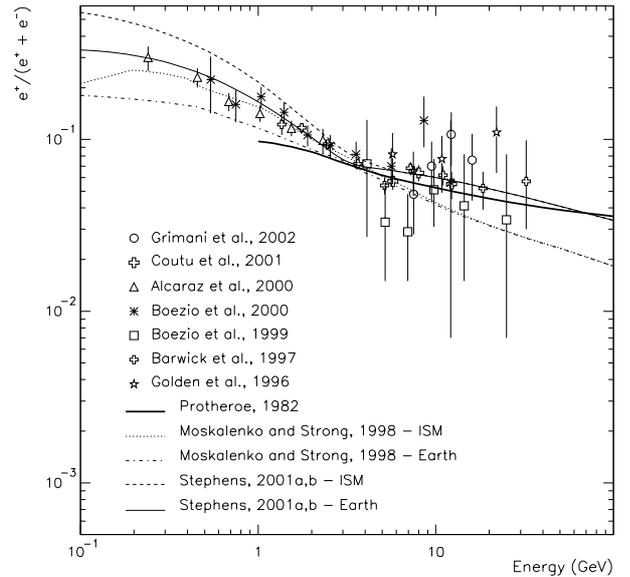


Fig. 2. Positron fraction observations published after 1995. The continuous thick line corresponds to the Protheroe (1982) calculations. The dashed and continuous lines represent, respectively, the fraction of positrons calculated in the interstellar medium and near the Earth by Stephens (2001a,b). The dotted (in the interstellar medium) and dot-dashed (Earth) lines correspond to the calculations of M&S (1998).

will indicate which model better represents the observations. Presently, it is reasonable to assume that the band where the M&S and Stephens calculations lie represents the uncertainty in the secondary positron component.

The drift of the $e^+/(e^+ + e^-)$ data points towards lower values in the last few years is believed to be due to the improvements with time of the detector performances and data analysis techniques for the rejection of protons and electrons against positrons.

The Muller and Tang (1987) experiment claimed a rejection efficiency against protons of 3×10^{-4} but the electron-positron separation was carried out using the east-west asymmetry in the geomagnetic cut-off rigidity and therefore, no cross check was possible on the actual charge of the positron candidates. The Golden et al. experiments (1987, 1994) included a magnetic spectrometer. However, in Golden et al. (1987) the positron-proton separation was made on the basis of the particle first interaction points in a shower counter. This technique left a quite large uncertainty on proton background ranging between 10 and 50% for the selected positron sample. Golden et al. (1994) presented a rejection factor against protons of 4.2×10^{-5} but, unfortunately, those data were affected by large statistical errors.

All recent experiments include magnetic spectrometers for electron background subtraction and present proton rejection factors with respect to positrons of better than 10^4 . The TS93 (Golden et al. 1996), CAPRICE (Boezio et al. 1999; Boezio et al. 2000) and HEAT (Barwick et al. 1997; Coutu et al. 2001) experiments claim, respectively, rejection factors of 3×10^4 , 10^5 – 10^6 and better than 10^5 . The MASS2 experiment (Grimani et al. 2002) presents an upper limit of background contamination on the positron sample of 1% at 95% CL.

Above 5 GeV practically all data points lie above the M&S calculations and the majority also above the Stephens calculation, being consistent with a possible positron excess.

3. Positron production at the pulsar polar cap

It is interesting to verify whether recent measurements are consistent with those phenomena suggested as sources of positrons during the 1990s. PBH with masses of 10^{15} g formed in the early Universe might have evaporated during the present epoch, producing electron-positron pairs. This process is supposed to contribute to the overall positron flux mainly below 1 GeV, and therefore it cannot explain the excess of e^+ above a few GeV (Carr & MacGibbon 1998).

Cobalt 56 has a half-life of 77 days. When this nuclide decays in young supernova remnants, positrons deposited in the supernova envelope can be reverse-shock accelerated. The predictions of this model lie above present $e^+/(e^+ + e^-)$ measurements beyond 10 GeV (Skibo & Ramaty 1993), meaning that the correct normalization remains to be determined even if this process cannot be excluded. The flat Galaxy rotation curves suggest that a substantial amount of dark matter exists, allowing the stars to be bound in the galactic disk. One possibility is that WIMPs populate the galactic halo (see for example Grimani 2000). The annihilation of WIMPs would have produced positrons with energies dependent on the particle mass. On the basis of the early data, WIMPs had to present masses larger than 30 GeV (Turner & Wilczek 1990). As an example, it was suggested that WIMPs as neutralinos in supersymmetric models might have annihilated into W^+W^- and Z^0Z^0 pairs followed by W^+ or Z^0 decay into positrons (Kamionkowski & Turner 1991).

Recently, the HEAT experiment data (Barwick et al. 1998; Coutu et al. 2001), affected by smaller statistical errors compared to the other measurements, seem to present an excess of e^+ between 7 and 10 GeV. The Kamionkowski and Turner scenario would have predicted an analogous feature on the $e^+/(e^+ + e^-)$ ratio but at higher energies. Therefore, either there is no feature in the data beyond a change of slope and no strong dip is present above 10 GeV or other processes such as neutralino-(electron sneutrino) annihilation might take place (Kane et al. 2001).

Future collider experiments at Fermilab and CERN might confirm or constrain these possibilities.

It must be stressed that when the HEAT data are compared to the Stephens calculations instead of the M&S calculations (Fig. 2) no feature can be seen and a very good agreement can be observed both at low and high energies. There are 3 data points in the range 5–9 GeV where the variation from Stephens' model in both directions is a little larger than expected based upon the experimental error bars; nonetheless, Stephens' model does capture the mean trend of the data.

Another phenomenon that was indicated as a possible source of positrons is the photon-photon pair production by diffuse γ rays having energies larger than 100 GeV with optical and UV radiation. The role that this process plays for a star like the sun is absolutely negligible, but it might be important to the positron flux on the Earth if there are enough hot giant stars

with associated γ -ray sources in the Galaxy (Mastichiadis et al. 1991).

In the following it is shown how the most recent positron fraction measurements help in limiting the PB in the Galaxy by considering the positron production at the pulsar polar cap as the only process to be added to the secondary interstellar e^+ above a few GeV.

Up to now, eight gamma-ray pulsars (Crab, B1509-58, Vela, B1706-44, B1046-58, B1952-32, Geminga, B1055-52) have been discovered. Two principal models have been suggested for gamma production at the pulsars. Polar-cap models (Daugherty & Harding 1996), where electromagnetic cascades are produced at the pulsar polar-cap and outer-gap models, where photons are generated by electrons accelerated in the outer magnetosphere in vacuum gaps within a charge-separated plasma (Cheng et al. 1986a,b). Different cut-off energies in the pulsar photon spectra observations are expected on the basis of the two models (De Naurois et al. 2002). The GLAST experiment that will observe gamma-ray sources between 10 MeV and 100 GeV might solve this problem in the next five years.

In the polar-cap models the pulsar rotation induces very high electric fields above the polar cap that accelerate outer-layer particles. The electrons move along the star magnetic field lines and produce synchrotron radiation. Emitted photons are converted into e^+e^- pairs and the shower develops.

Harding & Ramaty (1987) have calculated the positron production rate in the galaxy from pulsar polar-cap electromagnetic cascades above 3 GeV:

$$F_{e^+PC}(E) = 8.6 \times 10^{39} b_{30} r_{e^+} B_{12}^{-0.7} \left(\frac{t_{\max}}{10^4 \text{ yr}} \right)^{0.15} E^{-2.2} \text{ s}^{-1} \text{ GeV}^{-1}, \quad (1)$$

where: b_{30} is the PB normalized to a rate of $1/(30 \text{ yr})$; r_{e^+} is the ratio of positrons to gamma rays produced by a pulsar; B_{12} is the pulsar magnetic field normalized to $3.2 \times 10^7 (PP)^{0.5}$ G, P being the pulsar period and t_{\max} the interval of time during which the pulsar remains active for positron production. The dependence of $t_{\max}^{0.15}$ has been determined on the basis of the observed pulsed gamma-ray luminosity from young pulsars. Outer gap models indicate different gamma-ray luminosities and, consequently, do not explain observations so naturally (see Harding 2000 and references therein). The positron production rate reported in Eq. (1) corresponds to the energy differential flux shown in Fig. 3 when the calculations are carried out by using the parameters of the Crab nebula ($B_{12} = 3.8$ and $t_{\max} = 10^4$ years).

It has to be stressed that even if a polar-cap model will be found consistent with future, accurate measurements, the PB is the only parameter that needs to be determined by other observations.

Various estimates have been made of the PB. Lyne, Manchester & Taylor (1985) suggest that $1/PB$ ranges in the interval 30–120 years, consistently with the supernova explosion rate. Lorimer et al. (1993) find a $1/PB$ ranging between 125 and 250 years on the basis of a Monte Carlo simulation of the galactic pulsar population. Hansen (1999) indicates that a supernova explosion rate of $(10^2 \text{ yr})^{-1}$ is consistent with the hypothesis

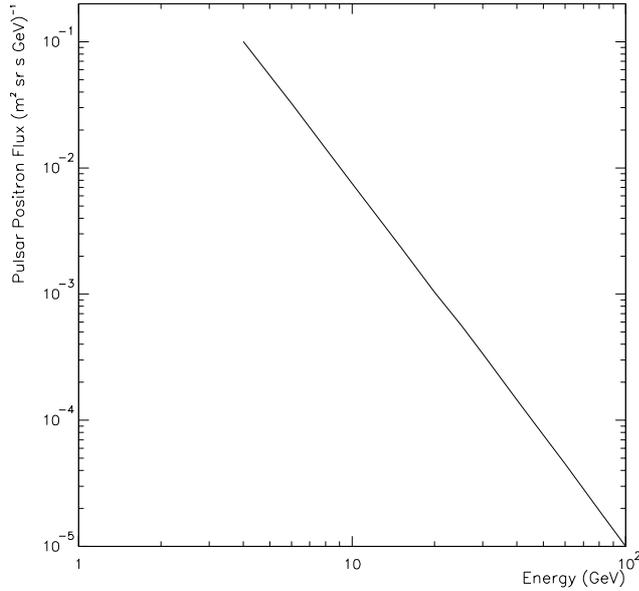


Fig. 3. Calculated positron energy differential flux resulting from the e^+ production in the pulsar polar-cap electromagnetic cascades. The characteristics of the Crab pulsar have been used in the calculations.

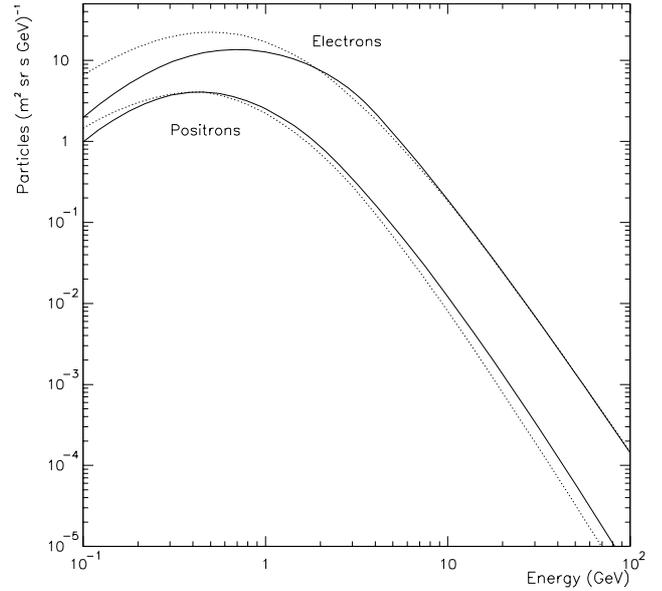


Fig. 4. Electron and positron differential energy spectra at the Earth according to the calculations of M&S (dotted lines) and Stephens (continuous lines).

of hypernovae (collapse of massive stellar cores giving rise to very energetic events).

Cosmic-ray positron measurements above 5 GeV allow us to set a limit to the PB in our galaxy when the e^+ interstellar component is taken into account.

On the basis of old positron fraction measurements the lower limit on the PB was one pulsar born every 60 years (Grimani 1996).

In order to check how the most recent measurements and calculations of the secondary positron flux in the interstellar matter have changed this scenario, the total expected $e^+/(e^+ + e^-)$ ratio above 4 GeV has been determined by adding the polar-cap positron flux to the secondary component according to the calculations of M&S and Stephens. In Fig. 4 the electron and positron fluxes calculated at the Earth by M&S (dotted lines) and Stephens (continuous lines) are shown.

The results are reported in Fig. 5. In this figure, dotted lines represent the calculations by M&S and continuous lines represent those by Stephens when the pulsar polar-cap positron fraction has been added.

The upper two curves have been found by considering a PB of one pulsar born every 30 years for the polar-cap model calculations. The band of predictions lies above almost the whole set of available data, showing that a PB for the polar-cap model must be smaller than once every 30 years. The region between the lower two curves correspond to a PB of one pulsar born every 250 years. Many more data lie in between the region of acceptable values but more data are above than below the mentioned region. Finally, the dashed region corresponds to the predictions of the pulsar polar-cap model when a PB of every 200 years is considered. This value best fits all measurements within the prediction region of 4–40 GeV. Measurements indicate a possible small excess of positrons with respect to the Stephens calculations, while a PB of at least one pulsar born

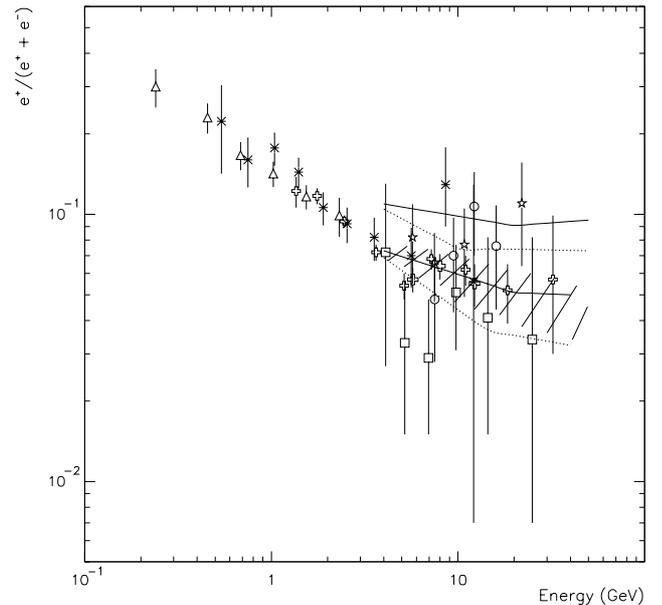


Fig. 5. Positron fraction measurements published after 1995 compared to the calculations of M&S (dotted lines) and Stephens (continuous lines) to which positrons from pulsar polar-cap cascades are added by considering a PB of one pulsar born every 30 years (region between the two upper curves), 200 years (dashed region) and 250 years (region between the two lower curves). The dashed region best-fits the data.

every 60 years would be required by the M&S calculations (Grimani et al. 2002). By considering the region of the predictions as a whole, an error of 50% can be conservatively set, i.e. we estimate that the PB is one pulsar born in the Galaxy every 200 ± 100 years.

4. Outer gap positron production and PB

In outer gap models, electrons and positrons are accelerated by a potential drop of the order of 10^{15} eV and generate gamma rays through synchrotron radiation or inverse Compton scattering. Electron-positron pairs are then produced by photon-photon interactions. These pairs generate secondary photons and, from them, further generations of electron-positron pairs are created until e^\pm energies are exhausted. Chi et al. (1996) have estimated the overall contribution to the interstellar positron flux produced in the pulsar magnetosphere. Outer gap positron production is supposed to be observable only below 1 GeV where the solar activity modulates the electron and positron fluxes. As a result, it is very difficult to obtain any hint from observations about this process. Above a few GeV, only polar-cap positron production plays a role. Depending on the actual fraction of pulsars presenting positron production in outer gaps, the PB estimate reported above may undergo some changes. In particular, if positron production in outer gaps is significant, the PB might be higher with respect to that determined only on the basis of the uncertainty on the secondary positron production in the interstellar medium.

It can be conservatively assumed that all pulsars present polar-cap and outer-gap positron production. If the energy lost by the star is equally shared among these two processes, the contribution to the positron flux per star above 2 GeV will also be approximately reduced by a factor of two. The PB would be increased, consequently, to about one pulsar born every 100 years but it would still remain in the range indicated above.

It is worthwhile to stress that if accurate future positron measurements show no excess of e^+ with respect to the secondary component above a few GeV, it can be deduced that either (i) the outer gap positron production overcomes that from polar caps or that (ii) $1/\text{PB}$ is larger than 200 years per pulsar birth. In the first case, a search for pulsed photon emission from young pulsars, such as the Crab pulsar, could test this possibility. In the second case, positron measurements would then indicate that $1/\text{PB}$ is well above any other estimate carried out until now with different methods.

5. Conclusions

The $e^+/(e^+ + e^-)$ ratio measurements published in the last few years have been compared to the most recent theoretical calculations of the e^+ interstellar secondary component and to the predictions of the positron production models in gamma-ray pulsar magnetosphere.

If electromagnetic cascades at the pulsar polar cap are considered as the only process that can generate positrons other than the secondary component above a few GeV, recent positron measurements indicate a PB in the Galaxy of one pulsar born per 200 ± 100 years. It has also been shown that even in the case of a non-negligible production of positrons in pulsar outer gaps a PB compatible with the above result is found.

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