Aspects of cosmic-ray positron astrophysics

Catia Grimani[1]

***Abstract*— Cosmic-ray $e^+/(e^+ + e^-)$ data indicate pair production in the pulsar magnetosphere as one of the most promising sources of positrons above 10 GeV. On the other hand, braking index observations suggest that energy loss mechanisms different from electromagnetic occur at the pulsars. In particular, we focused on the role of debris disks from Supernova fallback material. We find that present cosmic-ray positron observations remain consistent with a pulsar origin even in the case young pulsars lose energy via interactions with debris disks within measurements and model uncertainties.**

The detection of gravitational waves emitted by planetary systems would help in estimating the actual fraction of pulsars surrounded by these systems. Future, high sensitivity space interferometers might lead to this detection.

I. INTRODUCTION

Cosmic-ray positrons are mainly produced in proton and nucleus interactions in the interstellar medium (ISM; 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 (for a review see, for example, [3]), pair production in the pulsar magnetosphere appears to be one of the most promising ([4] hereafter H&R; [5]; [6]). We estimated the average parameters of mature pulsars (magnetic field and period) consistent with the assumption of e^+ and e^- production at the polar cap in addition to the secondary component ([7]; [8] and references therein).

In spite of precious clues on pulsar physics gathered from e^+ measurements, results were vitiated by large error bars affecting available positron data.

The PAMELA experiment observations on $e^+/(e^+ + e^-)$ ratio will help in solving this problem. PAMELA is gathering data since June 2006 at solar minimum during a negative polarity period with an unprecedented precision. Negative polarity epochs represent optimum conditions to study any possible excess of cosmic-ray positrons with respect to the secondary component. In fact, during negative polarity periods the Global Solar Magnetic Field affects positive particles more than negative ones (see for example [9] and references therein).

PAMELA preliminary results on the $e^+/(e^+ + e^-)$ ratio below 10 GeV [10] seem to confirm that the Moskalenko & Strong ([11] hereafter M&S) calculations reproduce well observations when the whole effect of solar modulation, including drift, is taken into account [8]. Therefore, no extra positron components need to be claimed below 10 GeV. In particular, no features are found near 6 GeV [12]. Conversely, an increase of the positron fraction above 10 GeV is found by PAMELA as well [13]. In spite of these encouraging clues, it is mandatory to wait for the final results of this experiment to be published before to discuss a quantitative comparison with the average trend of previously most accurate and precise data.

We point out that the estimates of positron fluxes produced in the pulsar magnetosphere are generally carried out assuming that pulsars lose energy via electromagnetic processes only. However, braking index observations indicate more than one energy loss mechanism [14]. Debris disks from Supernova fallback material surrounding young pulsars might play an important role ([15] hereafter MP&H). In this work we investigate if available positron measurements are compatible with this last suggested scenario. Preliminary results were presented in [16]. Detectability of gravitational waves possibly emitted by planetary systems surrounding pulsars are studied as well. In a future work we aim to investigate if disks interacting with the pulsar magnetosphere might be sources of gravitational waves as well.

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 indicate that electromagnetic showers are produced in the pulsar magnetosphere [17]. Polar cap and outer gap models were proposed to explain this evidence (see for example H&R; [18]). The MAGIC and GLAST 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 [8] shows that the positron fraction observations are compatible with a secondary origin of positrons (M&S) when solar modulation, including drift of opposite charge particles in the heliosphere, is considered and an additional component of electrons and positrons is added above a few GeV. In fig. 1 we have reported the most accurate measurements of the positron fraction gathered during the last two solar cycles (references to data are in [8]). The solid line indicates our prediction for the PAMELA experiment assuming a modulation parameter of 450 MV/c.

The e^+ and e^- in excess with respect to the secondary components are found consistent with the model of pair production at the polar cap of young pulsars by H&R when a normalization factor of 0.9 is applied to both particle fluxes [5]. 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 ([18]; [8] and references therein). Average mature pulsar magnetic fields of a few × $10^{12} G$ and periods ranging between 200 and 300 ms allow us to reproduce the trend of the observed positron fraction above a few GeV properly scaling

---

[1] Institute of Physics, University of Urbino, INFN Sez. Florence, Via S. Chiara, 27, 61029 Urbino (PU), Italy, catia.grimani@uniurb.it

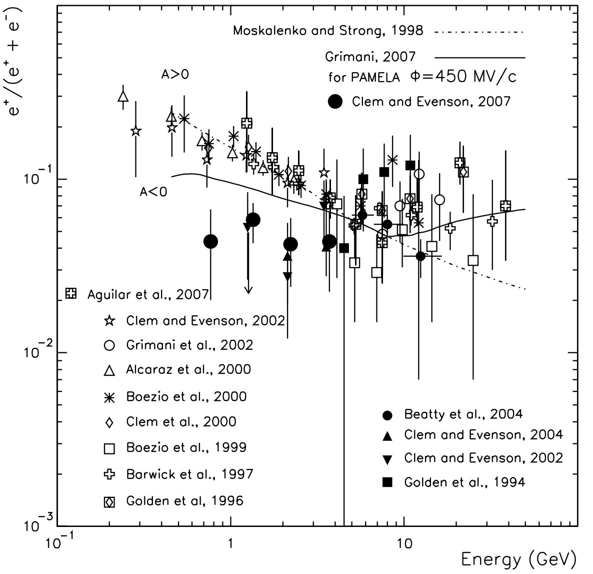

Fig. 1. Positron fraction measurements gathered during the last two solar cycles. The dot-dashed curve represents the expected trend for the positron fraction at the time of the PAMELA experiment in case of positive polarity conditions [11]. The continuous line corresponds to a negative polarity period and therefore represents the actual expected trend for the PAMELA data. Above 10 GeV extra components of e^+ and e^- from the pulsar polar cap were added [8].

the H&R results [7]. These parameters are found consistent with both average radio and gamma-ray pulsar observations [8].

Büshing e al. [19] have suggested that nearby pulsars only such as Geminga and B0656+14 generate extra positrons observed near Earth. The characteristics of these pulsars are close to our estimates and it is plausible that close pulsars contribute more than far ones. However, an e^+ contribution at a few tens of GeV from more distant pulsars cannot be excluded [20].

Gao, Jiang & Zhang [6] have shown that outer gap models are compatible with recent e^+ and e^- observations as well.

A. *PULSAR OBSERVED BRAKING INDICES*

Pulsar secular spin-down is represented by

$$\dot{\Omega} = -K\Omega^n \tag{1}$$

where the braking index, n, is defined as it follows

$$n = -\frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2} \tag{2}$$

In equation 2 Ω is the pulsar angular speed and $\dot{\Omega}$ and $\ddot{\Omega}$, its first and second derivatives, respectively.

In case pulsars are subject to the action of an electromagnetic torque only, n is expected to be 3 [21].

Conversely, all unambiguously measured pulsar braking indices are smaller than 3 as it can be observed in table I [14]. Various scenarios were proposed to explain this evidence and all of them were found plausibly consistent with observations. We recall the following ones: pulsars might not be a point dipole [22]; the pulsar spin down might be affected by its relativistic wind [23]; by a time varying magnetic moment [24]; by friction or propeller torque from a Supernova fallback disk (MP&H). Moreover, many authors (see for example [25], [26]) have suggested that gravitational wave emission due to pulsar ellipticities might play some role. The advanced LIGO and Virgo experiments will allow us to shed light on this last process even if pulsar ellipticities are expected to cause gravitational wave emissions during the early stage of a pulsar life only [21]. The present limit set by LIGO to the Crab pulsar ellipticity is of a few × 10^{-4} which constrains the gravitational wave luminosity to be less than 6% of the observed spin-down luminosity [27].

It is worth to investigate if the hypothesis of pulsar energy losses different from electromagnetic is consistent with e^+ and e^- cosmic-ray observations within the assumption of pair production in the pulsar magnetosphere taking measurement and model errors into account. In particular, friction of debris disks from Supernova fallback material and pulsar magnetosphere might increase the pulsar spin down.

TABLE I

PULSAR OBSERVED BRAKING INDICES. ERRORS IN PARENTHESES ARE REFERRED TO THE LAST DIGIT [14].

Pulsar	n
J1846-0258	2.65(1)
B0531+21	2.51(1)
B1509-58	2.839(3)
J1119-6127	2.91(5)
B0540-69	2.140(9)
B0833-45	1.4(2)

III. THE ROLE OF DEBRIS DISKS AROUND PULSARS

The first unambiguous discovery of a planetary system, different from ours, was claimed by Wolszczan and Freil in 1992 [28] for the millisecond pulsar PSR1257+12. It was suggested that planet formation was originated from the Remnant of the Supernova that generated the pulsar. A debris disk was detected around the millisecond pulsar 4U 0142+61 of 10^6 years as well [29].

MP&H have developed a model for young radio pulsar spin down caused by energy losses due to the torque of a disk surrounding the pulsar produced by the ejecta fallback. MP&H applied their model to 5 young pulsars, 3 of them being γ- ray pulsars such as Crab and Vela. In particular, they were able to reproduce the Crab parameters within 30% of the observed values assuming a debris disk mass fallback of 3 $\times 10^{16}$ - 10^{17} g/s. Alpar [30] has shown that the MP&H model explains the $P\dot{P}$ plot as well, where P is the period and $\dot{P}$ is the period derivative of the observed Galactic radio pulsar sample.

In table II we report the characteristics of the debris disks on the basis of the MP&H model and of the observed disk surrounding 4U 0142+61.

TABLE II
DEBRIS DISK CHARACTERISTICS.

Internal Radius (theoretical)	2000 km
External radius (theoretical)	200000 km
Internal Radius (observed)	2.02×10^6 km
External radius (observed)	6.75×10^6 km
Mass (observed)	5.97×10^{28} g
Mass fallback (theorethical)	3×10^{16} - 10^{17} $g\ s^{-1}$
Temperature (observed)	1200 K
Age (observed)	10^6 years

The amount of energy loss via electromagnetic processes ($\dot{E}_{em}$) with respect to that lost because of the presence of a debris disk ($\dot{E}_{DD}$) in Crab is reported in equation 3.

$$\frac{\dot{E}_{em}}{\dot{E}_{DD}} = 25 \left(\frac{\dot{M}}{10^{16} g s^{-1}} \right)^{-1} \tag{3}$$

Between 12% and 29% of the Crab energy loss might be due to pulsar interaction with a surrounding debris disk. The luminosity (L_{e_+}) of positrons produced at the polar cap of young pulsars is proportional to B_{12} $P^{1.7}$ where B_{12} is the magnetic field of the pulsar in terms of 10^{12} G and P is the pulsar period in seconds (H&R). The estimate of the parameters of mature pulsars contributing to interstellar electrons and positrons was carried out normalizing properly the results obtained by H&R for young pulsars without considering the possible role of debris disks [7]. Therefore, the magnetic fields of young pulsars such as Crab and Vela might be between 6% and 16% lower than those estimated by H&R (E_{em} is proportional to B^2). Consequently, the positron flux per mature pulsar estimated by [8] should be reduced accordingly. This uncertainty lies within the range of the allowed values of the pulsar parameters estimated by Grimani of the order of 30% for the pulsar period or a factor of two for the magnetic field from e^+ measurement best fit. We conclude that the hypothesis of the presence of debris disks around young pulsars is consistent with the possibility of pulsar polar cap origin of electron and positron pairs.

The positron flux measurements carried out by PAMELA will allow us to confirm or to reject the possibility discussed here. In particular, it will be possible to discriminate between positron extra components showing (such as for pulsar origin) or not (such as for supersymmetric particle annihilation origin) a power-law trend versus energy. Moreover, precious clues will be provided by absolute flux normalization within a few % measurement statistical uncertainties that might be useful to estimate the pulsar energy losses due to electromagnetic processes.

In the following Section we study the possible gravitational wave energy loss from planets and debris disks orbiting pulsars. Detection of gravitational waves from these systems would give valuable hints about the presence of debris disks in a large sample of galactic pulsars producing a major step forward with respect to individual observations.

These measurements along with positron fraction data will allow us to set severe upper limits to pulsar energy losses due to electromagnetic processes.

IV. GRAVITATIONAL WAVES FROM PULSAR PLANETARY SYSTEMS

The gravitational energy loss of pulsar-planet systems is [21]:

$$L_{gw} = \frac{32}{5} \frac{G^4}{c^5} M^3 \frac{\mu^2}{a^5} \tag{4}$$

where, M is the sum of the pulsar (M_1) and planet (M_2) masses ($M = M_1 + M_2$) and μ is the reduced mass $[M_1 M_2/(M_1 + M_2)]$. We call a the radius of the orbit of the planet around the pulsar.

The keplerian angular velocity is:

$$\Omega^2 = \frac{GM}{a^3} \tag{5}$$

For the pulsar PSR1257+12 and its two large planets, for example, M_1 is, typically, 2.8×10^{30} kg and M_2 is 1.67×10^{25} kg and 2.03×10^{25} kg. The two planets lie at 0.47 and 0.36 AU from the pulsar, respectively [28]. The energy losses via gravitational wave emission are 1.84×10^5 J/s and 1.03×10^6 J/s and the keplerian angular velocities are 7.3×10^{-7} Hz and 1.09×10^{-6} Hz.

These results can be compared to that of the Sun-Earth system characterized by an energy loss of about $200 J/s$ with an angular velocity of 1.99×10^{-7} Hz .

More in general, since planetary systems are supposed to form beyond hundreds of thousands kilometers from the pulsars [31], we estimate the upper limit to the gravitational energy losses in case all observed disk matter would form one only planet orbiting the pulsar. Minimum distances of these planets from pulsars were considered in table III for Keplerian orbital frequency (Ω) estimate. The expected emitted gravitational wave frequencies (2ν) and energy losses from planets surrounding pulsars appear in table IV.

TABLE III
KEPLERIAN ORBIT CHARACTERISTICS OF PLANETARY SYSTEMS AROUND PULSARS

Planetary system dimensions (km)	Ω (Hz)
$> 8\times10^5$	$<6.04\times10^{-4}$

TABLE IV

GRAVITATIONAL WAVE FREQUENCY AND ENERGY LOSSES FROM CIRCUMPULSAR PLANETARY SYSTEMS

2 ν (Hz)	L$_{gw}$ (J/s)
$< 1.92\times10^{-4}$	$<1.24\times10^{16}$

In order to estimate the amplitudes of gravitational waves emitted by planets surrounding pulsars we assume a system of reference in spherical coordinates (r,θ,ϕ) where an observer is positioned at a distance r from the center of mass of the system being $r{>}c/\Omega$. The two wave polarization amplitude are [32]:

$$h_+ = -\frac{1}{r}\frac{G^2}{c^4}\frac{2M_1M_2}{a}(1+cos^2\theta)cos[2\Omega(t-r)-2\phi] \quad (6)$$

$$h_\times = -\frac{1}{r}\frac{G^2}{c^4}\frac{4M_1M_2}{a}cos\theta sin[2\Omega(t-r)-2\phi] \quad (7)$$

On the xy plane $cos\theta = 0$ and no cross polarization is found. The amplitude of the gravitational wave associated becomes:

$$h_o = -\frac{1}{r}\frac{G^2}{c^4}\frac{4M_1M_2}{a} \quad (8)$$

Considering typical pulsar, debris disk masses and distances of planets from the pulsars given above, we obtain:

$$h_o = -\frac{1}{r}4.59\times10^{-7}m \quad (9)$$

Wave amplitude are at the most three orders of magnitude larger than that produced by the Earth around the Sun.

The frequencies of gravitational waves possibly emitted by planetary systems around pulsars might barely lie in the LISA space interferometer band (10^{-5}-10^{-1} Hz) [33]. The LISA sensitivity at these low frequencies is still uncertain but the maximum estimated mission lifetime of 10 years from 2018 will limit severely the distance of detectable sources because of the requirement $r > c/\Omega$. In other words, it is unlikely that LISA might lead to the detection of gravitational waves emitted by phoenix pulsars collecting planetary systems from Supernova explosions. However, this might happen with future space interferometers.

V. CONCLUSIONS

Cosmic-ray e^+ measurements indicate that below 10 GeV positrons are of secondary origin only, produced essentially by protons and nuclei interacting in the ISM. Above this energy a positron excess with respect to the secondary origin is indicated by the average trend of the data. This excess is compatible with positron production at the polar cap of middle aged pulsars. This scenario remains valid even in the case young pulsars are surrounded by Supernova fallback debris disks.

The detection of gravitational waves from planetary systems or, possibly, from disks with future space interferometers would allow us to estimate the fraction of young pulsars surrounded by these systems. This datum will allow us to better constrain the role of various pulsar energy loss mechanisms and to reduce the uncertainty on positron fluxes produced in the pulsar magnetosphere.

REFERENCES

[1] C. Grimani *et al.*,"Measurements of the absolute energy spectra of cosmic-ray positrons and electrons above 7 GeV," A&A, 392, pp. 287–294, 2002.
[2] C. Grimani, "Pulsar birthrate set by cosmic-ray positron observations," A&A, 418, pp. 649–653, 2004.
[3] S. Coutu *et al.*, "Cosmic ray positrons: Are there primary sources?," Astropart. Phys., 11, pp. 429–435, 1999.
[4] A. K. Harding and R. Ramaty, "The pulsar contribution to galactic cosmic ray positrons," in *20th Int. Cosmic Ray Conf. (Moscow)*, vol. 2, 1987, pp. 92–95.
[5] C. Grimani, "Upper limit to the cosmic-ray positron flux generated at the pulsar polar cap," in *29th Int. Cosmic Ray Conf. (Pune)*, 2005.
[6] Q. Gao, Z. Jiang and L. Zhang, "Possible contribution of mature γ-ray pulsars to cosmic-ray positrons," Chin. J. A&A, 8, pp. 87–95, 2008.
[7] C. Grimani, "Cosmic-ray and SEP physics with the LISA missions," in *20th Eur. Cosmic Ray Symp. (Lisbon)*, " 2006.
[8] C. Grimani, "Constraints on cosmic-ray positron excess and average pulsar parameters," A&A, 474, 339–343, 2007.
[9] C. Grimani and M. Fabi, "Parameterization of galactic proton and helium fluxes for future space missions," in *Ionizing Radiation Detection and Data Exploitation Workshop (ESA-ESTEC)*, 2007.
[10] P. Picozza for the PAMELA collaboration, XXth Rencontres de Blois, May 18th-23rd, 2008.
[11] I. V. Moskalenko and A. W. Strong, "Production and propagation of cosmic-ray positrons and electrons," Ap. J. 493, pp. 694-707, 1998.
[12] J. J. Beatty *et al.* "New Measurement of the Cosmic-Ray Positron Fraction from 5 to 15 GeV," Phys. Rev. Lett., 493, pp. 241102–241105, 2004.
[13] M. Boezio *et al.*, for the PAMELA collaboration, 34th ICHEP, Philadelphia, July 29th-August 5th, 2008.
[14] M. A. Livingstone *et al.*, "A Braking Index for the Young, High-Magnetic-Field, Rotation-Powered Pulsar in Kes 75," astro-ph/0601530
[15] K. Menou, R. Perna and L. Hernquist, "Disk-assisted spin-down of young radio pulsars," Ap. J., 554, pp. L63–L67, 2001.
[16] C. Grimani, 2nd European Interplanetary Science Congress, Potsdam August 19th-25th, 2007.
[17] M. De Naurois *et al.*, "Measurement of the crab flux above 60-GeV with the CELESTE Cherenkov telescope," Ap. J., 566, 343–357, 2002.
[18] L. Zhang and K. S. Cheng, "Cosmic-ray positrons from mature gamma-ray pulsars," A&A, 368, pp. 1063–1070, 2001.
[19] I. Büshing *et al.*, "Constraints on the lepton content of PWN from the local CR positron spectrum," in *30th Int. Cosmic Ray Conf. (Merida)*, 2007.
[20] A. M. Atoyan, F. A. Aharonian and H. J. Völk, "Electrons and positrons in the galactic cosmic rays," Phys. Rev. D, 52, pp. 3265–3275, 1995.
[21] S. L. Shapiro and S. A. Teukolsky, Black Holes, White Dwarfs and Neutron Stars (Wiley-Interscience, New York, 1983).
[22] A. Melatos, "Spin-down of an oblique rotator with a current-starved outer magnetosphere," MNRAS, 288, 1049–1059, 1997.
[23] F. C. Michel and W. H. Tucker, "Pulsar Emission Mechanism," Nature, 223, pp. 277–279, 1969.
[24] R. D. Blandford and R. W. Romani, "On the interpretation of pulsar braking indices," MNRAS, 234, pp. 57P–60P, 1988.
[25] A. Giazzotto, S. Bonazzola and E. Gourgoulhon, "Gravitational waves emitted by an ensemble of rotating neutron stars," Phys. Rev. D, 55, pp. 2014–2023, 1997.
[26] C. Palomba, "Pulsars ellipticity revised," A&A, 354, pp. 163–168, 2000.

[27] B. Abbott *et al.*, “Beating the spin-down limit on gravitational wave emission from the Crab pulsar,” astro-ph/08054758

[28] A. Wolszczan and D. A. Frail, “A planetary system around the millisecond pulsar PSR1257 + 12,” Nature, 355, pp. 145–147, 1992.

[29] Z. Wang, D. Chakrabarty and D. L. Kaplan, “A debris disk around an isolated young neutron star,” Nature, 440, pp. 772–775, 2006.

[30] M. A. Alpar, A. Ankay and E. Yazgan, “Pulsar spin-down by a fallback disk on the P-$\dot{P}$ diagram,” Ap. J., 557, pp. L61–L64, 2001.

[31] J. M. Cordes and R. M. Shannon, “Rocking the Lighthouse: Circumpulsar Asteroids and Radio Intermittency,” astro-ph/0605145v1

[32] V. Ferrari, M. D’Andrea and E. Beri, “Gravitational waves emitted by extrasolar planetary systems,” astro-ph/0001463

[33] ESA-SCI(2007) 1 Lisa Pathfinder: Einstein’s Geodesic Explorer. The science case for LISA Pathfinder LISA Pathfinder Science Working Team