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Constraints on the lepton content of PWN from the local CR positron spectrum

I. BÜSCHING[1], O. C. DE JAGER[1], M.S. POTGIETER[1], C. VENTER[1]
[1]*Unit for Space Physics, North-West University, Potchefstroom*
fskib@puk.ac.za

Abstract: Geminga is a nearby pulsar with an age of 3.42×10^5 yr and a spindown power of 3.2×10^{34} erg/s at present. B0656+14 has comparable spindown power, with an age of 1.11×10^5 yr and a distance of 290 pc. The winds of these pulsars had most probably powered PWNe that broke up less than about 100 kyr after the birth of these pulsars. Assuming that leptonic particles accelerated by the pulsars were confined in the PWN and got released into the interstellar medium on breakup of the PWN, we calculate the contribution of these particles to the locally observed cosmic ray electron and positron spectra. Our calculations show that within the framework of our model, the local CR positron spectrum imposes constraints on pulsar parameters for Geminga and B0656+14, e.g. the pulsar period at birth, and also the local interstellar diffusion coefficient for CR leptons.

Introduction

Geminga and B0656+14 are the closest pulsars with intrinsic ages in the range of 100 kyr to 1Myr [10]. They both have spindown powers of the order 3×10^{34} erg/s at present. The winds of these pulsars had most probably powered pulsar wind nebulae (PWNe) that broke up less than about 100 kyr after the birth of the pulsars.

Assuming that leptonic particles accelerated by the pulsars were confined in the PWNe and got released into the interstellar medium on breakup of the PWNe, we calculate the contribution of these particles to the locally observed cosmic ray electron and positron spectra.

Our calculations show that within the framework of our model, the local CR positron spectrum imposes constraints on pulsar parameters for Geminga and B0656+14, e.g. the pulsar period at birth, and also the local interstellar diffusion coefficient for CR leptons.

The Positron LIS

The CR positron spectrum has been measured by several groups in the last decades. In Fig. 1 we show some recent measurements at the top of the atmosphere and also the local interstellar spectrum (LIS) as derived from modulation studies.

The heliospheric modulation of cosmic ray electrons and positrons is primarily caused by four mechanisms: convection by the solar wind, diffusion because of turbulence in the heliospheric magnetic field (HMF), gradient and curvature drifts caused by the global structure of the HMF, and adiabatic energy losses. The latter is large for cosmic ray nuclei and causes at Earth characteristically shaped modulated spectra below kinetic energy $E <\approx 200$ MeV, with the differential intensity proportional to E^{+1}.

This process is so effective that irrespective of the spectral slope of the LIS of cosmic ray nuclei with $E <\approx 200$ MeV, the modulated spectra at Earth will have a E^{+1} form at these energies (e.g. [11]). LIS's for cosmic ray nuclei at these low-energies will therefore be observed only when spacecraft crossed the heliopause into the interstellar medium [6]. However, for electrons and positrons the energy losses are significantly less because they spend much less time in the expanding solar wind as relativistic particles before reaching Earth than e.g. galactic protons. The result is that at $E <\approx 200$ MeV, modulated electron and positron spectra at Earth will already exhibit spectral slopes closely resembling that of the LIS.

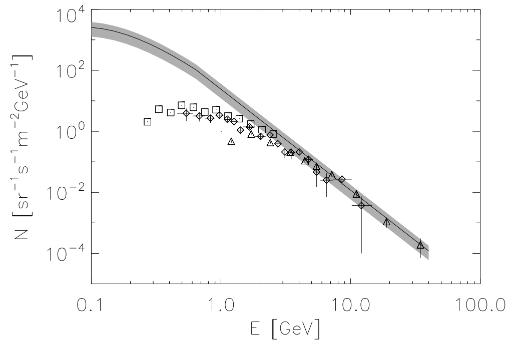

Figure 1: Positron flux at Earth from [1] (boxes), [3] (diamonds) and [5] (triangles) and the local interstellar positron spectrum as inferred from solar modulation studies (solid line). The grey band marks the possible range of the LIS [13].

Positrons from PWN

The relatively high surface magnetic fields of 1.63e12 G and 4.66e12 G for Geminga and B0656+14, respectively, imply copious pair production in the magnetospheres of these pulsars, even more when they were young, leading to a significant amplification in the number of injected electrons and thus also to a number of positrons comparable to that of the electrons. Within the framework of polar cap (PC) pulsar models, a single primary electron released from the stellar surface will induce a cascade of electron-positron pairs, and we model this amplification by introducing a multiplicity M'.

We assume that the electrons and positrons from the pulsar are re-accelerated at the pulsar shock, and model the particle spectrum by a power law with spectral index of 2, and with a maximum energy of

$$E_{\rm max} \quad = \quad \epsilon e \kappa \sqrt{\left(\frac{\sigma}{\sigma+1}\right)\frac{L_{\rm sd}}{c}}, \qquad (1)$$

where κ the compression ratio at the shock, $L_{\rm sd}$ the spindown power, and σ the magnetization parameter. This maximum energy stems from a condition on particle confinement: we require that the ratio between the Lamour radius and the radius of the pulsar shock should be less than a fraction ϵ. We assume that ϵ = 0.01 – 1, $\kappa = 3$, and use σ =0.01 – 1 ([14] propose a value of $\sigma = 0.1$ for Vela-like pulsars).

The fraction of the spindown power deposited in particles is

$$\eta_{\rm part} \quad = \quad \frac{1}{1+\sigma}. \qquad (2)$$

We assume that these particles are confined in the PWN for a time T, after which they are released into the surrounding interstellar medium. A break in the leptonic spectrum is enforced to take the maximum energy losses in the PWN into account:

$$E_{\rm b} \quad = \quad \frac{422}{B_{\rm PWN}^2 T} \quad [{\rm erg}], \qquad (3)$$

where $B_{\rm PWN}$ is the magnetic field inside the PWN measured in units of Gauss. Thus we have for the source function (at the PWN radius)

$$Q(E) = K \begin{cases} (E/E_{\rm b})^{-2} & ,{\rm for}\ E < E_{\rm b} \\ (E/E_{\rm b})^{-3} & ,{\rm for}\ E > E_{\rm b} \end{cases} .$$

One might expect that Q describes electrons and positrons occurring in equal abundances, and that the eventual positron spectrum would be $Q/2$. However, simulations of ultrarelativistic shock-waves in proton-electron-positron plasmas by [2] showed that the energy of positrons might dominate that of electrons when they are non-thermally accelerated, depending on the upstream flow energy of the ions. [9] observed a significant increase in the flux of the Vela PWN's outer arc, similar to the brightening of the Crab's wisps. If this brightening is due to ion cyclotron waves, we might plausibly expect that the presence of ions in PWN might be universal, so that ions will also be found in Geminga. Thus, Q might in some cases be regarded as the full positron spectrum.

We normalize Q by using the condition that the following equations have to be valid at any time

$$\int_{E_{\rm min}}^{E_{\rm max}} Q'(E,t)dE \quad = \quad \frac{M' I_{\rm GJ}}{e} \qquad (4)$$

$$\int_{E_{\rm min}}^{E_{\rm max}} Q'(E,t)EdE \quad = \quad \eta_{\rm part} L_{\rm sd}(t), \qquad (5)$$

with $Q'(E,t) = K' E^{-2}$ the particle spectrum at the pulsar wind shock.

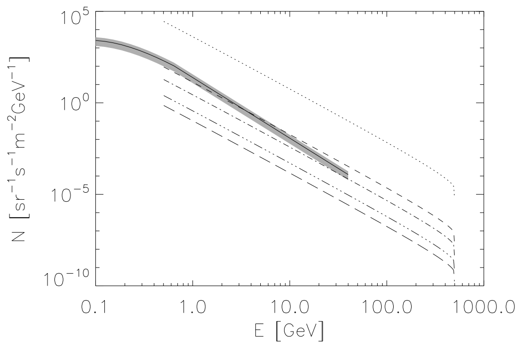

Figure 2: Expected CR positron spectra for $k_0 = 0.13\,\mathrm{kpc}^2\mathrm{Myr}^{-1}$, $\sigma = 0.1$, $T = 12\,\mathrm{kyr}$ and for birth periods of P_0=1 ms (dotted), 14 ms (dashed), 35 ms (dash-dotted), 70 ms (dash-trippledotted) and 100 ms (long-dashed) compared to the positron LIS (solid line).

Conservation of particles relates Q' and Q:

$$\int_0^T \int_{E_{\min}}^{E_{\max}} Q'(E,t)\,dE\,dt = \int_{E_{\min}}^{E_{\max}} Q(E)dE. \quad (6)$$

We estimate the lower energy $E_{\min}$ by assuming that it should be similar to the inferred value of the Crab. Using a value of 500 MeV for $E_{\min}$, Eq. (4,5) also yield the multiplicity M' at a given time. The choice for $E_{\min}$ stems from the fact that this is also the energy at which the positron LIS starts to bend over.

In Eq. (4), $I_{\rm GJ}$ represents the Goldreich-Julian current:

$$I_{\rm GJ} \approx 2c\rho_{\rm GJ}A_{\rm PC} \approx \frac{B_{\rm s}\Omega^2 R^3}{c} = \sqrt{6cL_{\rm sd}}, \quad (7)$$

with $\rho_{\rm GJ}$ the Goldreich-Julian charge density ([8]), and $A_{\rm PC} \approx \pi R_{\rm PC}^2$ the PC area.

For a pulsar magnetic field that does not decay (i.e. $\dot{P}P^{n-2} = \dot{P}_0 P_0^{n-2}$), the time-evolution of $L_{\rm sd}$ is given by [12]

$$L_{\rm sd}(t) = L_{\rm sd,0}\left(1+\frac{t}{\tau_0}\right)^{-\frac{n+1}{n-1}}, \quad (8)$$

with $n = 3$ representing a dipolar magnetic field, and $\tau_0 = P_0/((n-1)\dot{P}_0)$, P_0 the birth period, and $\dot{P}_0$ the period's time-derivative at pulsar birth (The subscript '0' denotes quantities at pulsar birth). These quantities are connected to the spindown luminosity at birth via

$$L_{\rm sd,0} = -\frac{4\pi^2 I\dot{P}_0}{P_0^3}. \quad (9)$$

The total number of particles in the PWN before breakup, is then

$$N_e = \iint Q'(E,t)\,dE\,dt. \quad (10)$$

The propagation of CR electrons and positrons in case of the diffusion coefficient k being spatially constant, is described by

$$\frac{\partial N}{\partial t} - S = k\Delta N - \frac{\partial}{\partial p}(b\,N), \quad (11)$$

where N is the differential number density, S the source term and b the rate of energy losses. A Green's function solving Eq. (11) can be found in the literature (e.g. [7]). For a functional form of the diffusion coefficient $k = k_0 p^{3/5}$ and the energy losses $b = b_0 p^2$ (i.e. synchrotron and inverse Compton losses) the Greens's function is

$$G = \delta\left(t - t_0 - \frac{E_0^{-1} - E^{-1}}{b_0}\right) \times \frac{\exp\left(-\frac{(\vec{r}-\vec{r_0})^2}{\lambda}\right)}{b_0 E^2(\pi\lambda)^{1.5}}, \quad (12)$$

and $\lambda = 10\left(k_0\left(E^{-0.4}\right) - E_0^{-0.4}\right)/b_0$. For a point source at $\vec{r_s}$, with a spectrum $Q(E)$ as given by Eq. (3) releasing particles at a time t_s, the convolution can be done analytically, thus

$$N = \frac{\exp\left(-\frac{(\vec{r}-\vec{r_0})^2}{\lambda}\right)}{b_0^2 E^2(\pi\lambda)^{1.5}E_0^2} \times \left(\left(\Theta\left(E_{\rm b}-E_0\right) - \Theta\left(E_0 - E_{\min}\right)E_0^{-2}\right) + \left(\Theta\left(E_{\max}-E_0\right) - \Theta\left(E_0-E_{\rm b}\right)E_0^{-3}\right)\right) \quad (13)$$

where $E_0 = E/\left((t-t_s)\,b_0 E + 1\right)$. We calculated the contribution from Geminga and B0656+14 to the positron LIS for distances of 157 pc [4] and 290 pc [10] respectively. The results for different birth periods of this pulsar are plotted in Fig. 2 where we compare our calculation with the positron LIS discussed earlier. From Fig. 2 one can see that for the chosen set of parameters, we can rule out $P_0 < 35$ ms for Geminga.

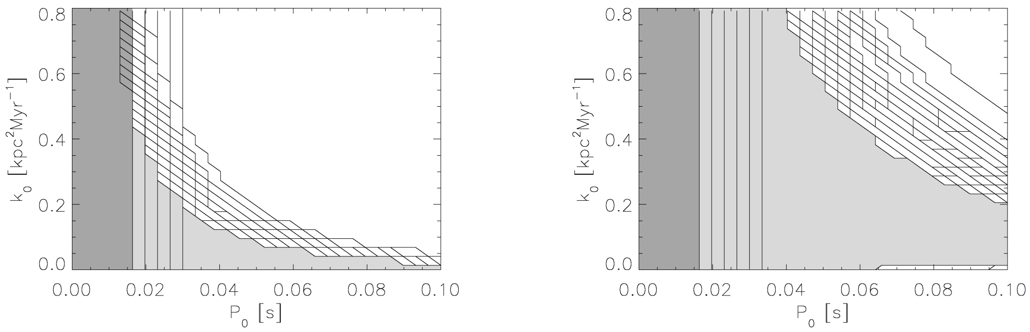

Figure 3: Tolerable magnitude k_0 of the interstellar diffusion coefficient against the pulsar birth period P_0 (white region) for different model parameters (T =20 kyr, 0.001< ϵ <0.1, 0.01< σ < 1), for Geminga (left) and B0656+14 (right) assuming the contribution of each pulsar is 50% to the CR positron flux as shown in Fig. 1 for . Note that we can exclude pulsar birth periods $<\approx$ 20 ms (dark grey region), as these produce lepton numbers in the PWN in excess of $N_e = 10^{52}$ which have not been observed.

Conclusions

We have shown that one can expect a non neglible CR lepton component in the LIS from nearby pulsars. In the context of our model we are able to constrain the permissible P_0-k_0-space (Fig. 3). This opens a new way to obtain information on the properties of young, nearby pulsars and will therefore help to refine the models for pulsars and PWN. In this study we did not discuss the magnitude of the contribution of secondary positrons to the LIS. Reliable estimates of the contribution from a prominent, nearby point source may be obtained from measurements of spatial anisotropies stemming from a local gradient in the CR positron distribution.

Acknowledgements

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