Signatures of a middle aged, nearby pulsar in the cosmic ray lepton spectrum?

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***Abstract*. PSR B0656+14 is a middle aged, nearby pulsar, with a spin down power of 3.8e+34 erg/sec. The wind of this pulsar most probably had powered a PWN that broke up about less than 100 kyr after the birth of the pulsar. Assuming that leptonic particles accelerated by the pulsar 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. In particular, we investigate the possibility that the recent PAMELA results on the positron fraction and the feature in the local cosmic ray lepton spectrum at about 400 GeV, as reported by the ATIC collaboration, can be attributed to PSR B0656+14.**

***Keywords*: pulsars, pulsar wind nebulae, cosmic ray leptons**

I. Introduction

The recent data from the PAMELA [1] and ATIC [7] experiments sparked a series of papers explaining these results either by contributions of positrons to the local interstellar cosmic ray (CR) spectrum by dark matter (DM) or pulsars. Focusing here on pulsars, we argue that at the present, our knowledge about particle acceleration at pulsars as well as of the local Galactic CR propagation is still limited, i.e. the recent results for CR electrons and positrons constrain pulsar and propagation models. This paper will thus not be another attempt to explain the data by contributions of pulsars to the local CR lepton flux but rather to highlight the caveats in doing so.

II. Pulsars as Particle Accelerators

Modelling the acceleration of particles at pulsars and subsequent injection of these particles into the interstellar medium, one may look at three scenarios: young pulsars (after the breakup of their pulsar wind nebulae)[4], mature pulsars [8],[23] and millisecond pulsars. While the latter have been shown to give, if any, only a marginally contribution to the local CR lepton flux [5], [19], both young pulsars and mature γ-ray pulsars may indeed contribute to the locally observed CR lepton flux.

A. Energy Budget

Before discussing the acceleration of particles by pulsars, it is instructive to look for the available energy budget. The available energy of a pulsar is its rotational energy. The power which is transferred to radiation and particles is given by the spin down of the pulsar. The spin down power of a pulsar is given by

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

[18] where the characteristic decay time τ_0 is given by

$$\tau_0 = P_0/((n-1)\dot{P}_0) \qquad (2)$$

with $n = 3$ for a magnetic dipole field of the pulsar.

P_0, $\dot{P}_0$ are the period and its derivative at pulsar birth

$$L_{\rm SD,0} = \left|-\frac{4\pi^2 I\dot{P}_0}{P_0^3}\right|. \qquad (3)$$

assuming the magnetic field of the pulsar does not decay, this can be written as

$$L_{\rm sd,0} = \left|-\frac{4\pi^2 I\dot{P}P}{P_0^4}\right|. \qquad (4)$$

It is easily seen from Eq. 4 that given a small enough period, one can get an arbitrary large energy reservoir. 10 ms can be seen as the lower limit for P_0, while initial periods in the range ≈50–150 ms are not uncommon [10]. It is estimated that up to 40% of the pulsars may be born with periods in the range 100–500 ms [22].

B. Source Spectra

Several models have been put forward to describe the acceleration of CR leptons by pulsars (see e.g [17]).

1) Simple power law: The simplest approach is to assume that some fraction f of the spin-down power $L_{\rm SD}(t)$ is transferred to particles, which follow a power-law spectrum with index a

$$N(E) \quad = \quad \frac{L_{SD} f}{\int_{E_{\rm min}}^{E_{\rm max}} E^{a+1} dE} E^a. \qquad (5)$$

2) Model of Harding and Ramaty: [13] assume a positron spectrum similar to the γ-ray spectrum. They expect a positron spectrum from the pulsar of the form

$$N(E) = 2.3\times 10^{46}\Gamma\, B_{12}^{-0.7} t^{-0.85} E^{-2.2} {\rm s}^{-1}{\rm GeV}^{-1} \qquad (6)$$

Γ is the ratio of positrons to γ-rays, E the particle energy in GeV and B_{12} magnetic field in units of 10^{12}G.

3) Models of Chen, Zhang, Chi and Young: [8] and [23] look at particle acceleration at mature pulsars with ages larger than 100 kyr. In their models pulsars inject their monoenergetic wind into the interstellar medium. According to [23], γ-ray pulsars (i.e. $f = 5.5P^{26/21}B_{12}^{-4/7} < 1$, where P is the period of the pulsar and B_{12} its magnetic field in units of 10^{12} Gauss), accelerate electron positron pairs to the energy

$$E_{ep} \approx 0.1 \times 0.61\, f^{-1}\, (100\zeta)^{-1}\, P^{-7/3}\ \mathrm{GeV} \quad (7)$$

where

$$\zeta \approx 3.8 \times 10^{-4} f^{1/2} B_{12}^{7/12} P^{-19/12} \times \left(\frac{4\,(\pi/2 - \alpha)}{9}\right)^{-0.54}. \quad (8)$$

The particle flux in the wind is

$$N \approx 9.7 \times 10^{35}\, (100\zeta)^2\, f^2 B_{12}^2 P^{2/3} \mathrm{s}^{-1} \quad (9)$$

where α is the magnetic inclination, i.e. the angle between the axis of rotation and the magnetic axis. The above models predict very narrow electron positron spectra, suitable to model the ATIC peak.

4) Model of Büsching, deJager and Venter: From Eq. 1 it is clear that the available spin-down power (and thus the available energy that can be transferred to particles) is largest when the pulsar is still young. In fact, integrating Eq.1 over time for $n = 3$, it becomes clear that at $t = \tau_0$ the pulsar dissipated half of its total available rotational energy. One can therefore expect that the majority of particle acceleration at a given pulsar takes place for $t > \tau_0$. What is indeed observed are nebula of relativistic particles around many young pulsars, pulsar wind nebulae (PWN). There is also evidence, that these highly relativistic particles are confined in the PWN [9].

Assuming the particles from the pulsar are reaccelerated at the pulsar wind shock and then contained in the PWN until its breakup, [4] model the particle spectrum injected into the interstellar medium by the two middle aged, nearby pulsars B0656+14 and Geminga. Generalizing this model by assuming a broken power law particle spectrum at the pulsar shock [21]

$$Q'(E,t) = \begin{cases} k'(t)\left(\dfrac{E}{E_B}\right)^{-2} & \text{for } E > E_B \\ k'(t)\left(\dfrac{E}{E_B}\right)^{-1} & \text{for } E < E_B \end{cases} \quad (10)$$

keeping E_B a free parameter. The spectrum at the shock is normalised by the available energy deposited into particles

$$\int_{E_{\min}}^{E_{\max}} Q'(E,t) E dE = f_{\mathrm{part}} L_{\mathrm{SD}}(t). \quad (11)$$

The fraction of the spin down power deposited in particles

$$f_{\mathrm{part}} = \eta \frac{1}{1+\sigma} \quad (12)$$

can be expressed in terms of the magnetisation parameter

$$\sigma(t) = 0.003 \left(\frac{t}{1\,\mathrm{kyr}}\right)^{3/2}. \quad (13)$$

The maximum particle energy at shock is [21]

$$E_{\max} = \epsilon e \kappa \sqrt{\frac{\sigma}{\sigma+1}} \sqrt{\frac{L_{\mathrm{SD}}}{c}}, \quad (14)$$

where $\epsilon = r_L/r_{\mathrm{shock}} = 0.001 \ldots 0.1$. $\kappa = 3$ is the compression ratio at the shock and e the elementary charge.

The evolution of the particle spectrum in the PWN is governed by synchrotron losses

$$\frac{\partial Q(E,t)}{\partial t} - Q'(E,t) = \frac{\partial}{\partial E}\left(B_{\mathrm{PWN}}(t)^2 E^2 Q(E,t)\right) \quad (15)$$

where the mean PWN magnetic field is assumed to decay with time

$$B_{\mathrm{PWN}}(t) = \frac{1200}{(1+t/\mathrm{kyr})^2}\ [\mu\mathrm{G}]. \quad (16)$$

Under these assumptions, the particle spectrum in the PWN at time of breakup T is:

$$Q(E,T) = \int_0^T Q'(E_0,t_0) E_0^2 E^{-2} \Theta\left(E_0 - E_{\min}\right) \times \Theta\left(E_{\max} - E_0\right) dt_0, \quad (17)$$

with

$$E_0 = \frac{E}{E \int_t^{t_0} B_{\mathrm{PWN}}(t')^2 dt' + 1}$$

III. PROPAGATION OF COSMIC RAY LEPTONS

The propagation of CR leptons in the Galaxy is dominated by diffusion and energy losses due to synchrotron radiation in the Galactic magnetic field and can be described by the equation

$$\frac{\partial N}{\partial t} - S = \nabla \cdot (k \nabla N) - \frac{\partial}{\partial E}\left(b_0 E^2 N\right). \quad (18)$$

where b_0 is determined by the Galactic magnetic field.

In the case of pulsars, the source function is given by

$$S = Q(E,t)\delta\left(\vec{r} - \vec{r}_{\mathrm{source}}\right), \quad (19)$$

where $Q(E,t)$ is given by a model for particle acceleration at pulsars. The diffusion coefficient has an energy dependence of the form

$$k = k_0 \left(\frac{E}{1\ \mathrm{GeV}}\right)^{\delta} \quad (20)$$

where $\delta = 0.3 \ldots 0.7$ and k_0 are determined by fitting observed secondary to primary and radioactive secondary data. Depending on the model, k_0 is in the range $0.006\,\mathrm{kpc^2 Myr^{-1}}$ to $0.2\,\mathrm{kpc^2 Myr^{-1}}$ (e.g. [15]).

Although obtaining k_0 in this way is a well established procedure, we want to remark the following. First, obtaining k_0 from secondary to primary (e.g B/C) data only yields a correlation between k_0 and the halo height H [16]. This degeneracy can be broken by looking at radioactive to stable secondary ratios (e.g. ^{10}Be/Be). In doing so, one compares life times due to radioactive decay with the times scale of escape, the latter depends on the diffusion perpendicular to the Galactic disk. Thus the fitting of the observed chemical composition of CR by a propagation model measures primarily the propagation perpendicular to the Galactic disk, which not necessarily has to be the same as that in the Galactic plane. Second, to the best of our knowledge, all studies determining k_0 by fitting the observed chemical composition so far use 1D or 2D models. Nevertheless, it has been shown [6], that the primary component of locally observed CR flux may change at least by a factor of two depending on the local SN history, in case these objects are indeed the main sources of Galactic CR. The flux of the secondary component shows little or no variation. Thus, the observed secondary to primary ratios will depend on the local SN history. It may be necessary to focus on tertiary to secondary ratios when working with 2D propagation models.

In case of an infinite diffusion volume, Eq. 18 is solved by the Green's function

$$G = \delta\left(t - t_0 - \frac{E_0^{-1} - E^{-1}}{b_0}\right) \frac{\exp\left(-\frac{(\vec{r}-\vec{r_0})^2}{\lambda}\right)}{b(\pi\lambda)^{1.5}}, \quad (21)$$

with

$$\lambda = 4 \frac{k_0 \left(E^{\alpha-1} - E_0^{\alpha-1}\right)}{(1-\alpha)\, b_0}. \quad (22)$$

[3] (see also [2]).

IV. MODELLING THE CONTRIBUTION OF PULSARS TO THE LOCAL COSMIC RAY LEPTON SPECTRUM

If the source function of electrons and positrons accelerated at the pulsar and also the distance to this object is known, one can calculate the contribution of these particles to the locally observed CR spectrum with the help of Eq. 21. As discussed above, the magnitude of the diffusion coefficient in the Galactic plane is not well determined. Also, the spectrum of the particles injected into the interstellar medium strongly depends on the model used.

We focus now on the model of Büsching, deJager and Venter, as it considers particle acceleration at young pulsars, and thus, according to Eq. 1, promises the largest output of leptons. The parameters of this model span a wide parameter space. The pulsar birth period can be in the range ≈ 10 ms to 500 ms, E_B, is most probably in the range 10–1000 GeV, and the PWN life time T smaller 100 kyr. Within this parameter space in addition to the uncertainties in k_0, it is possible to produce a wide range of particle spectra at earth which can fit the data. In fact, some spectra even exceed the experimental constraints, so that we should be able to constrain the parameter space of this model.

V. EXPERIMENTAL DISCRIMINATION BETWEEN DARK MATTER AND PULSAR ORIGIN

If indeed the observed increase in the positron fraction is due to the pulsars B0656 and Geminga, the fact that those two pulsars are located about 7 degree apart on the sky in the outer Galaxy, we expect an anisotropy towards the galactic anticenter, as discussed in [4]. However, for DM we expect either an isotropic sky, or an anisotropy towards the galactic center region.

In the diffusion model, the anisotropy in the CR flux is given by [11]

$$\delta = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{3\, k\, |\nabla N|}{c\, N}. \quad (23)$$

For instantaneous injection at time t_i and distance r_i for a diffusion coefficient as given by Eq. 20, one arrives at

$$\delta = \frac{3}{2\, c} r_i\, b_0\, (\alpha - 1)\, E^{\alpha} \left(E^{\alpha-1} - E_0^{\alpha-1}\right)^{-1} \quad (24)$$

with

$$E_0 = E / \left((t - t_i)\, b_0 E + 1\right). \quad (25)$$

For $E \to 0$, Eq. 24 reduces to

$$\delta = \frac{3}{2c} \frac{r_i}{t_i}.$$

a result derived by [14] for energy independent diffusion. [4] find an anisotropy of a few percent above 10 GeV. We remark that one expects for $E < 10$ GeV a solar cycle dependent anisotropy that is due to modulation of CR electrons and positrons.

VI. SUMMARY

The ATIC report of an excess just below 1 TeV resulted in a wide interest in the interpretation of the signal. This signal is also supported by the PAMELA detection of an increase in the positron to electron ratio towards the energies where ATIC saw their excess above the general cosmic ray lepton (electron and positron) spectral background. If we assume that this effect is real, then we are left with two competing explanations: (i) Kaluza-Klein type particle, or, (ii) a local source(s) of electrons and the best candidate for the latter is a pulsar (with its wind nebula) since both the Kaluza-Klein and the pulsar interpretations require both electrons and positrons, probably in equal numbers.

Whereas the Kaluza-Klein explanation required the introduction of a boost factor of 200 in the volume production rate to explain the ATIC signal [7], the pulsar/PWN interpretation also involve a number of free parameters, such as the birth period and interstellar diffusion coefficient between the source and earth. In this paper we have discussed a few scenarios which can fit the observed data and we are left with more questions than answers!

Thus, at the moment it seems as if we are left with too many free parameters and uncertainties to make an unambiguous statement about the origin of the ATIC (or at least the PAMELA) signal, so that more work needs to be done on Dark Matter candidate particles, as well as the multiwavelength nature of pulsars and their wind nebulae. New approaches may also be required to remove some of the uncertainties involved.

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