Modelling of particle acceleration in the pulsar wind nebulae with bow shocks

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Abstract. The observations of the pulsar wind nebulae (PWNe) indicate the presence of efficient acceleration of positrons and electrons in these sources. The Fermi acceleration in the colliding shock flows can explain the observed hard synchrotron emission spectra of PWNe with bow shocks (BSPWNe). This may result in their maximal luminosities in the far ultraviolet (FUV; 1250 — 2000 Å, ∼ 6 — 10 eV) due to the synchrotron emission of pairs rather than due to the thermal emission of the shocked interstellar matter. Fine spectroscopic observations of sufficiently bright sources with Hubble Space Telescope could be applied to distinguish between these two scenarios. In this paper we simulate BSPWNe flows structure with the relativistic magnetohydrodynamic code PLUTO, consider particle transport and their synchrotron emission for a number of BSPWNe. We calculate the synchrotron FUV luminosities of these BSPWNe and discuss the prospective of their observation in FUV. We also consider possible contribution of PSR J1741-2054 to the positron excess detected by AMS-02 and PAMELA.

1. Introduction
The emission of pulsar wind nebulae with bow shocks (BSPWNe) notable for their multiform morphologies and hard spectral components [1, 2] can be produced in a few processes. Firstly, the interstellar matter heated at the bow shock can radiate in a number of spectral lines including far ultraviolet (FUV) lines. Secondly, particle acceleration at the termination shock (TS) of the pulsar wind (PW) forms the particle spectra $f(E) \propto E^{-s}$ with $s \sim 2.2$. These particles emit synchrotron radiation with photon indices $\Gamma = (s + 1)/2 \sim 1.6$ in the magnetic field of the pulsar wind nebula (PWN) separated from the shocked interstellar medium (ISM) by a contact discontinuity (CD). The typical scale of the latter is defined by the ram pressure balance

$$R_{cd} = \sqrt{\frac{\dot{E}}{6\pi \rho_{ism} u_{psr}^2 c}}, \quad (1)$$

where $\dot{E}$ is the pulsar spin-down power, $u_{psr}$ — its proper velocity, $c$ — the light velocity, $\rho_{ism}$ — the ISM mass density. Finally, energetic particles, whose mean free paths (mfps) are large enough to evade advection to the PWN tail, can cross the CD and invade into the shocked ISM (the mfp is understood as a typical distance between consequent scatterings at the turbulent magnetic field inhomogeneities). These ones can be involved in the Fermi acceleration in the colliding shock flows (CSFs). This reacceleration produces a hard spectrum with $s < 2$ below...
the energetic threshold where the mfp exceeds the nebular size. The synchrotron emission with $\Gamma < 1.5$ may explain the hard spectra of BSPWNe and their ultraviolet emission could be dominated by the synchrotron radiation of pairs due to peaking of their synchrotron luminosity.

Favouring any scenario for FUV radiation of BSPWNNe requires fine spectroscopic measurements and an accurate kinetic modelling of particle transport. It is possible only for quite bright FUV sources. Choosing the observation targets assumes preliminary simulations for various poorly constrained parameters. The particle acceleration modelling requires an adequate model of nebular plasma flows which can be performed using the relativistic magnetohydrodynamical (RMHD) modelling. For some aspects of BSPWN simulations see, e.g., the recent papers [3, 4].

In this paper we consider the kinetic modelling of synchrotron emission of BSPWNNe taking into account realistic models of their plasma flows structure. We discuss the dependence of their spectra and FUV luminosities on uncertain parameters and make some predictions about their detectability in FUV with Hubble Space Telescope. We consider PSR J1741-2054 as a possible source of positron excess detected by PAMELA and AMS-02 space observatories [5, 6].

2. Estimations and structure of flows

The energy $E_{\text{max}}$ of the spectral energy distribution (SED) maximum for particles accelerated in the CSFs depends on the conditions of their confinement in the source. Specifying the diffusion coefficient $D(E)$, one can write

$$D(E_{\text{max}}) = R_{cd} u_{\text{psr}}.$$  \hspace{1cm} (2)

The corresponding photon energy $\epsilon_{\text{max}}$ depends on the magnetic field (note: it does not match the synchrotron SED maximum, lying at higher energy matching the particle energy $E$ such that $s = -d \ln f/d \ln E = 3$). The magnetic field in the shocked PW $B_{\text{pwn}}$ was estimated in [7]:

$$B_{\text{pwn}} = B_{\text{pu}} \gamma_2 = \frac{\gamma_2}{u_2} \sqrt{\frac{\sigma}{1 + \sigma} \frac{E}{u_2}}.$$  \hspace{1cm} (3)

$$u_2^2 = \frac{8\sigma^2 + 10\sigma + 1}{16(\sigma + 1)} + \frac{1}{16(\sigma + 1)} \left[ 64\sigma^2 (\sigma + 1)^2 + 20\sigma (\sigma + 1) + 1 \right]^{1/2}.$$  \hspace{1cm} (4)

where $\gamma_2^2 = 1 + u_2^2$, $B_{\text{pu}}$ is the magnetic field upstream the TS (fields are in the observer frame) and the magnetization $\sigma = B_{\text{pu}}^2/4\pi n_w \gamma_w m_e c^2$ is the ratio of the Poynting energy flux to the kinetic energy flux carried by the PW, $\gamma_w$ is the cold PW Lorentz-factor, $n_w$ — particle number density just upstream the TS in the observer frame, $m_e$ is the electron mass.

The RMHD modelling shows that the typical TS radius $r_{ts}$ is close to the $R_{cd}$ value. We illustrate this in Figure 1, where we present the results of RMHD modelling of BSPWNNe performed using the numerical code PLUTO [8]. One can see the map of the BSPWN flows density obtained in a simulation of the supersonic motion of pulsar emitting the PW through the ISM. The PW was set up as described in details in [9]. Region A corresponds to the unshocked PW and indeed has a size of the order of the standoff distance (1) chosen as the unit length.

The magnetic field $B_{\text{bow}}$ (region C) which could be amplified by the current-driven instabilities produced by the cosmic ray protons accelerated at the shock [10–13] is bounded by the ram pressure $\rho_{\text{ism}} u_{\text{psr}}^2$ of the ambient flow streaming with velocity $u_{\text{psr}}$ in the pulsar rest frame.

Thus, $B_{\text{pwn}}$ could be constrained by setting $\dot{E}$, $\sigma$ and $r_{ts} \sim R_{cd}$. The latter as well as the estimated $B_{\text{bow}}$ depend on $u_{\text{psr}}$ and $\rho_{\text{ism}} = \zeta m_p n_{\text{ism}}$, where $m_p$ is the proton mass, $n_{\text{ism}}$ is the ISM number density, $\zeta$ $\approx 1.4$ is the chemical composition factor assuming the solar abundance. The most uncertain parameters are, likely, $\sigma$ and, unless the bow shock was detected, $n_{\text{ism}}$.

We fixed $\sigma = 0.1$ which is in consistence with the recent RMHD models of various PWNe [20] and calculated $\epsilon_{\text{max}}$ varying $n_{\text{ism}}$ for a number of pulsars. In the left panel of Figure 2 the
Figure 1. Simulated map of the flows mass density (in arbitrary units) of a BSPWN resembling nebula of PSR J1741-2054. Letters A-D denote the unshocked ultrarelativistic PW, the shocked PW, the shocked ISM and the unperturbed ISM, respectively, the black contour shows the approximate position of the PW termination shock.

Table 1. Parameters of considered sources: pulsar spin-down luminosities $\dot{E}$, proper velocities $u_{psr}$, distances to the sources $d$, the hydrogen column densities $N_H$. Data from [14–19]

| Source          | $\dot{E}$, erg s$^{-1}$ | $u_{psr}$, km s$^{-1}$ | $d$, pc      | $N_H$, cm$^{-2}$ |
|-----------------|-------------------------|------------------------|-------------|----------------|
| PSR J1741-2054  | $9.5 \times 10^{33}$    | $196 \pm 18$          | 380        | $1.2 \times 10^{21}$ |
| PSR B1929+10    | $3.9 \times 10^{33}$    | $177^{+5}_{-4}$       | $361^{+10}_{-8}$ | $1.7 \times 10^{21}$ |
| PSR B0823+26    | $4.6 \times 10^{32}$    | $194 \pm 41$          | 340        | $6 \times 10^{20}$     |
| PSR B1133+16    | $8.8 \times 10^{31}$    | $631 \pm 30$          | 360        | $1.5 \times 10^{20}$     |

results are shown for a few fast moving pulsars found the most prospective in terms of observing their nebulae in FUV: PSR J1741-2054, B1929+10, B0823+26 and B1133+26 (hereafter J1741, B1929, B0823 and B1133; see Table 1). In case of J1741 the bow shock is detected in Hα allowing to constrain $n_{ism} \approx 1.4$ cm$^{-3}$ [21]. In the following we present the simulated spectra of J1741 for this fixed value of $n_{ism}$ and B1929, B0823 and B1133 for a few reasonable values.

3. Modelling of particle spectra and emission

The kinetic modelling of particles and their emission spectra in BSPWNe requires simulation of particle transport in the nebula accounting for an adequate model of the nebular flows structure. We implemented this using the Monte-Carlo model described in [22–24]. The simulated particle spectra are illustrated in the right panel of Figure 2 and the synchrotron spectra — in the left panel of Figure 3. The Fermi acceleration in CSFs appear in all spectra. The hard components $f(E) \propto E^{-1}$ manifest themselves in growing $\nu F_{\nu} \propto \nu$. When $\nu$ approaches to $\nu_{max}$ the particle spectra gradually softens. The following falling in SEDs corresponding to the cutoff in the reaccelerated components is then changed by a typical PWNe spectrum with $\Gamma \sim 1.6$.

We normalized the fluxes via matching the modelled and observed X-ray luminosities. To our knowledge, no PWN are detected to date around B0823 and B1133, so we used the X-ray luminosities of the sources associated with the pulsars. The presented fluxes for B0823 and B1133 could be considered as the upper limits.
Figure 2. Left: the estimated energy of photons emitted by the particles gained maximal energy in the acceleration in CSFs in the magnetic field of the PWN (solid lines) and the shocked ISM (dashed lines) for various ISM number densities. Black horizontal lines are the bounds of the FUV range. Right: the smoothed simulated spectra of particles leaving the considered BSPWNe, where $n_{\text{ism}} = 0.1$ cm$^{-3}$ for PSR B1929+10, B0823+26, B1133+16 and 1.4 cm$^{-3}$ for PSR J1741-2054.

Figure 3. Left: the unabsorbed fluxes of synchrotron emission of BSPWNe produced by PSR J1741-2054 (red), B1929+10 (green), B0823+26 (blue) and B1133+16 (magenta). For the last three PSRs the results with different ISM number densities are shown by curves with different patterns. Right: the expected FUV synchrotron fluxes of the same BSPWNe. The unabsorbed and absorbed values are shown by circles and diamonds, respectively.

In the right panel of Figure 3 we present the predicted absorbed FUV fluxes. J1741 seems to be the most prospective target though rather a long exposure is still likely required. The synchrotron FUV luminosities of BSPWNe weakly depend on the ISM density in contrast with the emission of the shocked ISM gas whose emissivity scales $\propto n_{\text{ism}}^2$.

4. Positrons from PSR J1741-2054
PWNe produced by a few nearest pulsars could be responsible for the excessive flux of positrons in the cosmic rays detected by PAMELA [5] and AMS-02 [6] (see, e.g., [25]). PSR J1741-2054 with rather large $\dot{E} = 9.5 \times 10^{33} I_{45}$ erg s$^{-1}$, where $I_{45}$ is the moment of inertia of the neutron star in units of $10^{45}$ g cm$^2$, can produce a significant contribution to the observed positron
flux at sub-TeV energies. Indeed, the measured positron flux at sub-TeV energies $F \approx 20 \text{ GeV}^2 \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}$ or $5 \times 10^{-9} \text{ erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ corresponds to the positrons energy density $n_E = 4\pi F/cE \approx 4 \times 10^{-18} \text{ erg cm}^{-3}$. Assuming a spherically symmetric isotropic diffusion from a central source with the diffusion coefficient $D$, one can write $\frac{\eta E}{4\pi r^2} = -D \frac{\partial n_E}{\partial r}$ where $\eta$ is the fraction of $E$ converted by the PWN into the sub-TeV particles energy. Assuming $\eta = 2\%$ and $r = 380 \text{ pc}$, one obtains $D (0.35 \text{ TeV}) = 3.5 \times 10^{27} \text{ cm}^2 \text{s}^{-1}$ or $2 \times 10^{26} \text{ cm}^2 \text{s}^{-1}$ at 1 GeV if $D(E) \propto E^{1/2}$. This value of the local interstellar diffusion coefficient is consistent with the recent investigations [26, 27] assuming the isotropy of the local diffusion.

![Figure 4. The simulated flux of the positrons produced by PSR J1741-2054 compared with the AMS-02 data [6]](image)

We simulated the stationary diffusion of positrons from PSR J1741-2054 to the Earth taking the diffusion coefficient $D = 5.5 \times 10^{26} (E/1 \text{ GeV})^{1/2} \text{ cm}^2 \text{s}^{-1}$. We took into account the particle energy losses due to synchrotron and inverse Compton emission assuming $B_{\text{ISM}} = 3.6 \mu \text{G}$ and using the radiation fields described in [28]. The obtained positron flux for the Earth vicinities is presented in Figure 4. Full particle flux produced by the source carries about half of its spin-down luminosity. One can see that this source indeed can produce the observed positron excess at sub-TeV energies, while the excessive flux at lower energies (below $\sim 300 \text{ GeV}$) could be explained by a spiral arm model [29] as well as by a few other nearby pulsars [30].

5. Conclusions
In this paper we presented the results of kinetic modelling of particle acceleration and their synchrotron emission in a number of nebulae produced (or thought to be produced) by fast moving pulsars: PSR J1741-2054, B1929+10, B0823+26, B1133+16. We simulated their emission spectra and calculated their far ultraviolet luminosities for various number densities of the ISM. We found nebula of PSR J1741-2054 the most prospective far ultraviolet target though quite a long exposition would be likely required. We note that the dependence of the synchrotron FUV BSPWNe luminosities on the ISM number density is much weaker than $\propto n_{ism}^2$ expected when the FUV emission is produced by relaxation of atoms of shocked ISM gas. This implies that the nebulae propagating in the dilute mediums are better candidates for possible distinguishing between two different FUV emission mechanisms. We also simulated the propagation of the PW positrons from PSR J1741-2054 to the Earth and found that this source could be responsible for the excessive flux of positrons detected by AMS-02 and PAMELA at sub-TeV energies.
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