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Modelling of far ultraviolet emission of pulsar wind nebulae with bow shocks

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Abstract. The kinetic modelling of electron and positron acceleration in the colliding shock flows of pulsar wind nebulae with bow shocks allows to explain the nature of their hard particle spectra. The hard synchrotron emission produced by the accelerated particles can reach the far ultraviolet range (1250 - 2000 Å) providing the maximal luminosity of the bow shock nebulae in this range. In this paper the results of modelling of pulsar wind particles transport in the colliding shock flows in the bow shock nebulae of PSRs J1741-2054 and B1929+10 are presented. The results of the synchrotron emission modelling are confronted to the observations in order to estimate possible far ultraviolet luminosities of the discussed objects.

1. Introduction

Pulsars (PSRs) emitting the relativistic pulsar winds (PWs) and propagating through the ambient matter with a supersonic velocity produce pulsar wind nebulae with bow shocks (PWNe with BSs, BSPWNe). These objects differ from the PWNe of slowly moving PSRs morphologically as well as spectrally. Namely, the BSPWNe typically have a cometary shape with long trails of high energy emission. A number of BSPWNe appear as the sources of X-ray emission with hard photon indices $\Gamma < 1.5$ [1,2]. To explain these features of the synchrotron nebular emission the PW electrons and positrons spectra $f(E) \propto E^{-s}$ with s < 2 upto few hundred TeV are required. These spectra significantly differ from the typically inferred spectra with $s \sim 2.2 - 2.3$ thought to be produced at the termination shock (TS) of the PW. The hard positron spectra can be responsible for the positron fraction excess observed by PAMELA and AMS-02 detectors at the Earth orbit [3].

As it was shown in [4], the particle acceleration in the colliding shock flows (CSFs) between the TS and the BS can produce lepton spectra with $s \sim 1$ and explain the observed hard X-ray photon indices. The developed kinetic Monte Carlo model allows to reproduce the observed structure of PSR J0437-4715 nebula, whose bow shock with 10'' apex was detected in H α and far ultraviolet (FUV; 1250 - 2000 Å, 6 - 10 eV) observations but was not found in X-rays. The FUV emission might be generated either by the synchrotron emission of PW leptons accelerated in the CSFs zone or by the shocked ISM gas (see, e.g., [5]). To go for any of the alternatives one should use a detailed spectroscopy of the source.

Modelling of the PSR J0437-4715 nebula synchrotron emission (see [4, 6, 7]) shows that the formation of hard particle spectra in the CSFs causes a peak in the source luminosity at few eV.

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International Conference PhysicA.SPb/2019

Journal of Physics: Conference Series

Interestingly, this mechanism may result in maximal luminosities around FUV for a number of BSPWNe. In this paper we discuss particle transport and synchrotron emission modelling for BSPWNe of PSR J1741-2054 (hereafter J1741) and B1929+10 (hereafter B1929) and present the prediction of luminosities of these nebulae in FUV.

2. Model parameters

The detailed discussion of the Monte Carlo particle transport model in the BSPWNe is given in [4]. Here we discuss some important parameters of the model determining the spectral behaviour of the modelled sources.

The break in the BSPWNe spectra thought to be the product of the Fermi I type acceleration in the CSFs is defined by the maximal energy of the particles E_{max} confined in the CSFs zone and the magnetic field in the source. A simple estimate for E_{max} may be given by (1)

$$D\left(E_{max}\right) \approx u_{psr}R_{sh} \tag{1}$$

$$R_{cd} = \sqrt{\frac{\dot{E}}{6\pi\rho u_{psr}^2 c}} \tag{2}$$

where u_{psr} is the pulsar proper velocity, R_{sh} — the bow shock apex scale, which is of the order of the standoff distance R_{cd} – a typical scale of the BSPWNe, defined by the balance of the ram pressures of the PW and the ambient matter flow in the pulsar rest frame. In (2) \dot{E} is the pulsar spin-down power, ρ is the ambient medium mass density and c is the light velocity. Assuming that the strong large-scale fluctuations of the turbulent magnetic field determine the particle scattering in range $E < E_{max}$ one may use the Bohm-like diffusion coefficients in this range (see [4] and the references therein). Thus, to predict the spectral break frequency, one has to estimate the typical values of the magnetic field in the source and the standoff distance.

PSR J1741-2054 located at distance ~ 380 pc has a spin-down energy loss rate of $\dot{E} = 9.5 \times 10^{33} I_{45}$ erg s⁻¹ and the transverse velocity ~ 196 km s⁻¹ [8, 9]. Here I_{45} is the momentum of inertia of the neutron star in units of 10^{45} g cm². PWN produced by J1741 was observed in a number of optical filters as well as in X-rays [9–13]. The X-ray nebula has a cometary shape without any bow-like structure [9, 12]. The H α observations reveal a presence of a structure associated with a bow shock [10]. In contrast to the typical shape of such structures well approximated by the thin-shell solution of Wilkin (1996) [14], the head part of the H α bow shock is very flat and close to the pulsar. Romani et al. [10] associated this feature with the pulsar wind anisotropy and proposed to use Wilkin (2000) [15] solution for the bow shock shape. Brownsberger and Romani [11] obtained the particle number density in the vicinity of the nebula $n \sim 1.44$ cm⁻³. The standoff distance (2) estimated for this value $R_{cd} \sim 4 \times 10^{15}$ cm (~ 1″) is consistent with the observed structure of the nebula.

PSR B1929+10 located at distance ~ 361 pc with an estimated spin-down $\dot{E} = 3.9 \times 10^{33} I_{45}$ erg s⁻¹ has a transverse velocity ~ 177 km s⁻¹ [16]. Hui and Becker [16] performed a spatial analysis of the X-ray *Chandra* images of the PSR B1929+10 neighbourhood. They revealed a compact arc-like nebula resembling a bow shock. The brightness profile along the direction of the pulsar proper motion computed by the authors was confronted to the MARX [17] simulated point source model. The profile indicates the presence of the extended emission at least up to ~ 1" ahead the pulsar, consistent with their result for the estimated standoff distance $\theta_s = 1.13 \pm 0.02$ arcsec, considered as a lower bound. Misanovic et al. [18] also processed *Chandra* data and found an extended bow-like 9x5 arcsec nebula. They estimated the standoff distance to be around 3".

The magnetic fields in the source may be estimated as follows. On the one hand, a reasonable value of the PWN magnetic field B_{PWN} can be found from the results given in [19] for the PW magnetization parameter $\sigma \sim 10^{-2} - 1$ found in modern 2D-3D RMHD simulations of the

Journal of Physics: Conference Series

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Crab nebula, the Vela PWN, etc. (see, e.g., [20]). The same formulae allow to estimate the typical shocked pulsar wind velocity u, important for the emission modelling due to the Doppler boosting. On another hand, the corresponding Poynting flux as well as the energy flux carried by the particles escaping the source should not exceed the energetic budget of the system, given by the pulsar spin-down. We found reasonable $B_{PWN} \sim 75 \ \mu\text{G}$ for B1929 and $\sim 70 \ \mu\text{G}$ for J1741, and $u \approx 0.4c$. Our estimates of the PWN magnetic field are consistent with the estimates given by [9, 16]. The magnetic field downstream the BS should be rather a small fraction of the ambient matter flux ram pressure. Assuming that about 10% of the ram pressure is converted into the turbulent magnetic field, $\Theta = 15^{\circ}$ and 30° between the proper motion velocity vector and the plane of sky for J1741 and B1929, respectively, ambient matter density $n = 1 \text{ cm}^{-3}$ for B1929 and solar abundance, one may obtain about 60 μ G for J1741 and 50 μ G for B1929.



Figure 1. Top: simulated energy flux injected by the pulsar wind particles into the colliding shock flows zone at the termination shock (red) and carried away from the source by the accelerated particles (purple). Bottom: simulated synchrotron emission fluxes from the entire nebula (black), from the vicinities of the termination shock (red) and the bow shock (blue). Magenta curves show the simulated synchrotron emission flux from the modelled nebula where the particle acceleration in the colliding shock flows was suppressed.

To confront the modelling results with the observations the particle transport modelling is supplied with the simulation of the source emission spectra and the imaging of the source. The unabsorbed X-ray fluxes from the inner regions of the source are used to normalize the emission spectra. Namely, the unabsorbed fluxes from the arc-like feature (see [16]) for B1929 and from region 1 for J1741 [9] (both $\approx 2 \times 10^{-14} \text{ erg cm}^{-2} \text{ sec}^{-1}$) are used.

3. Modelling results

The results of the Monte Carlo particle transport modelling are presented in the top panel of Fig. 1. The red curves show the energy flux injected by the PW particles into the CSFs zone at the termination shock, while the purple curves demonstrate the energy flux carried by the particles leaving the source. One can see the formation of the hard components with s < 2 due to acceleration in the CSFs zone corresponding to a positive derivative of the plotted function. This spectral component yields a spectral break in the modelled unabsorbed synchrotron flux, shown in the bottom panel of Fig. 1. The red and blue curves show the unabsorbed fluxes from the vicinities of the termination and bow shocks, respectively, while the black curves correspond to the simulated unabsorbed flux from the entire source. As have been already announced, the acceleration in the CSFs makes the far ultraviolet range nearly the most luminous for both the sources. The model with the CSF acceleration predicts an order of magnitude higher FUV luminosities than the model where the CSF acceleration was suppressed by assuming fast particle diffusion outside the contact discontinuity between the colliding flows (magenta curves in the bottom panel of Figure 1).

According to the model, the unabsorbed FUV luminosity for B1929 is about 2.8×10^{29} erg s⁻¹. For J1741 one could expect 3×10^{29} erg s⁻¹. In Figure 2 the simulated synchrotron images of the unabsorbed FUV emission of the considered nebulae are presented.



Figure 2. The simulated synchrotron images of the modelled BSPWNe of PSR B1929+10 (left) and PSR J1741-2054 (right) in the FUV range (1250 - 2000 Å, 6.2 - 9.9 eV). The surface brightness is normalized to its maximal value. The cyan crosses mark the pulsars positions, while the white arrows show the pulsar proper motion direction.

Unfortunately for both the pulsars rather big values of nH are inferred, $nH > 1.7 \times 10^{21}$ cm⁻² for B1929 and about 1.2×10^{21} cm⁻² for J1741. The absorbed fluxes $F_{J1741} \approx 3 \times 10^{-15}$ erg cm⁻² s⁻¹ and moreover $F_{B1929} \approx 1 \times 10^{-15}$ erg cm⁻² s⁻¹ are likely too low to be detected by the Hubble Space Telescope (HST) at realistic exposures. This makes their detection with the HST in FUV quite unexpectable. However, these sources might be detected in the far ultraviolet range by the ultraviolet instruments of the next generation.

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4. Conclusions

In this paper the kinetic modelling of positron and electron transport in the bow shock nebulae of PSR J1741-2054 and B1929+10 after leaving the PW termination shock vicinity is discussed. The modelled particle spectra were used to simulate the synchrotron spectra and images of the nebulae. The far ultraviolet luminosities of the sources were calculated, and the absorbed far ultraviolet fluxes from these sources were estimated. The model predicts the absorbed flux $\sim 3 \times 10^{-15}$ erg cm⁻² s⁻¹ for the PSR J1741-2054 nebula and $\sim 1 \times 10^{-15}$ erg cm⁻² s⁻¹ for the PSR B1929+10 nebula. Assuming that the ultraviolet luminosity of the studied objects is indeed dominated by the synchrotron emission of the PW leptons their detection in the far ultraviolet range by the *Hubble Space Telescope* with realistic exposures is rather unexpectable. Nevertheless, these nebulae could be detected in the far ultraviolet range by the forthcoming ultraviolet missions with more sensitive instruments.

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