Hydrodynamics of interaction of pulsar and stellar winds and its impact on the high energy radiation of binary pulsar systems

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The hydrodynamics of the interaction of pulsar and stellar winds in binary systems harboring a pulsar and its impact on the nonthermal radiation of the binary pulsar PSR B1259-63/SS2883 is discussed. The collision of an ultrarelativistic pulsar wind with a nonrelativistic stellar outflow results in significant bulk acceleration of the shocked material from the pulsar wind. Already at distances comparable to the size of the binary system, the Lorentz factor of the shocked flow can be as large as $\gamma \sim 4$. This results in significant anisotropy of the inverse Compton radiation of accelerated electrons. Because of the Doppler boosting of the produced radiation, one should expect a variable gamma-ray signal from the system. In particular, this effect may naturally explain the reported tendency of a decrease of TeV gamma-ray flux close to the periastron. The modeling of the interaction of pulsar and stellar winds allows self-consistent calculations of adiabatic losses. Our results show that adiabatic losses dominate over the radiative losses. These results have direct impact on the orbital variability of radio, X-ray and gamma-ray signals detected from the binary pulsar PSR B1259-63/SS2883.

Keywords: HD; shock waves; pulsars: binaries

1. Introduction

Binary systems represent an important population of very high energy (VHE) sources. Presently this category comprises four objects [1–5]. At least one of them, PSR B1259-63/SS2883, is a binary pulsar system consisting of a 48 ms pulsar in an elliptic orbit around a massive B2e optical star [6]. The multiwavelength observations of the system [7–13] indicate correlations between different energy bands [14]. One of the interesting features of the high energy emission of PSR B1259-63/SS2883 is the behavior of the gamma-ray light-curve which deviates from the earlier theoretical predictions [15, 16]. The understanding of the nature/origin of the high energy radiation of this object is a quite complex issue. It requires not only proper modeling of the acceleration and radiation process in the context of multiwavelength properties of the source, but also detailed studies of the hydrodynamics of the interaction of the pulsar and stellar winds. Indeed, the particle acceleration regime and formation of energy distribution of relativistic particles after termination of the pulsar wind strongly depend on the dynamics of the flow. In this regard one should note that the recent attempts at explanation of the gamma-ray light-curve of PSR B1259-63/SS2883 [14, 17] contain assumptions which are closely linked to the hydrodynamics of the system. For example, the density changes along current lines determine the adiabatic loss rate in the flow. The flow bulk motion is also responsible for the particle advection (escape) from the system. The nonradiative losses caused by these processes may have a strong impact on the energy spectrum.
and light-curve of gamma-rays [17]. Therefore, any self-consistent treatment of the high energy radiation of the system requires hydrodynamic calculations of key parameters characterizing the interaction of two winds. This concerns, in particular, the magnetic field. The magnetic field is expected to be nonhomogenous in the pulsar wind nebulae [18]. The calculations of the spatial distribution of the strength of the magnetic field generally requires a proper magnetohydrodynamical (MHD) approach. However, in the case when the the impact of the magnetic field on the dynamics of plasma is not dramatic, it can be treated hydrodynamically within a “frozen-in” approach. Below we assume the influence of the magnetic field to be weak and we discuss the impact of hydrodynamics characterizing the collision of pulsar and stellar winds on the high energy radiation of the system. The results are based on the recent hydrodynamic calculations of Bogovalov et al. [19] conducted through two different approaches using a relativistic code in the “pulsar zone” and a nonrelativistic code in the “optical star” region. It is assumed that initially both the pulsar and stellar winds expand radially.

2. Hydrodynamics of interaction of relativistic and nonrelativistic winds

The discussion below concerns the regions of linear scales comparable to the size of the binary system (because the variable synchrotron and IC radiation components are predominantly generated in this region). The results are based on the hydrodynamical calculations reported by Bogovalov et al. [19]. The properties of the steady-state flow basically depend only on one parameter, namely on the wind ram pressure ratio \( \eta \) [19]:

\[
\eta = \frac{\dot{E}_{sd}}{Mcv_0}.
\]

Here \( \dot{E}_{sd} \) is the pulsar spindown luminosity; \( M \) and \( v_0 \) are the stellar mass loss rate and the stellar outflow velocity, respectively (both winds are assumed to be isotropic). In the particular case of PSR B1259-63/SS2883 the parameter \( \eta \) is expected to be within \( 10^{-2} - 1 \) [19]. Depending on the value of \( \eta \), the structure of the flow may significantly change. It is demonstrated in Figs. 1 and 2 for \( \eta = 1 \) and \( \eta = 0.05 \) (the color represents the flow bulk Lorentz factor). Figures 1 and 2 show that at distances comparable to the size of the binary system, the bulk Lorentz factor of the shocked flow may be as high as \( \gamma \sim 4 \). Because of Doppler boosting, this should result in a significant anisotropy of nonthermal emission of relativistic particles. Moreover, the large bulk Lorentz factors imply significant adiabatic losses. Indeed, the full energy per particle \( \gamma w/n \) is conserved along the flow line (here \( w \) and \( n \) are the enthalpy and particle densities). Thus the acceleration of the flow is reduced to the transfer of the thermal energy to the bulk motion, i.e. to adiabatic losses. Below we compare the adiabatic loss time to other relevant time-
scales, the particle escape time and IC cooling time. Note that all these time-scales depend, unlike the overall structure of the flow, on the separation distance \( D \) between stars.

As long as the post-shock flow velocity is close to the speed of light \( c \), the advection time scale can be estimated as

\[
t_{\text{esc}} = \frac{D}{c}.
\]  

(2)

It is convenient to express all times in the unit of \( D/c \). In Figure 3 we show the IC cooling time for three different separations, which correspond to \( \pm 100 \), \( \pm 20 \) and 0 days to the periastron passage. The calculations are performed for the following parameters: temperature of the optical star \( T_\ast = 2.2 \times 10^4 \) K; eccentricity of the orbit \( e = 0.87 \); periastron separation \( D_0 = 9.6 \times 10^{12} \) cm. As it follows from Fig. 3, the inverse Compton cooling time \( t_{\text{ic}} \gg D/c \), i.e. the radiative cooling time is much larger than the particle escape time, especially at large separation distances (obviously, \( t_{\text{ic}} \propto D^2 \), due to decrease of target photon density).

Although it is not possible to obtain, from first principles, the adiabatic loss rate, the \( D \)-dependence of the adiabatic cooling time can be defined. Interestingly, the adiabatic loss time has a \( D \)-dependence similar to \( t_{\text{esc}} \). Indeed, since adiabatic losses, which occur between two points on the current line, depend only on the ratio of densities in these points, one obtains

\[
t_{\text{ad}} \propto D,
\]

(3)

since the traveling time between these two points is proportional to \( D \). This allows us to determine the \( D \)-dependence of the ratio of IC to nonradiative cooling time:

\[
\frac{t_{\text{ic}}}{t_{\text{esc/ad}}} \propto D.
\]

(4)

Thus, in a case of collision of two isotropic winds small separation distances are more preferable for VHE gamma-ray production. Although, we note here that it does not necessarily imply higher observable fluxes, due to the anisotropy related to the Doppler boosting of the produced emission.

Generally, the adiabatic loss rate is not homogeneous in the flow. In Figure 4 we show typical dependences of adiabatic cooling time, obtained with numerical simulation, along current lines for two cases: \( \eta = 0.03 \) and \( \eta = 0.1 \) (please note that sharp peaks/deeps in this figure are numerical artifacts). These calculations were performed along current lines close to the contact discontinuity in the “pulsar zone”. The calculations show that for the flow structure predicted by the hydrodynamical calculations, one should expect very fast (compared to the IC cooling time) adiabatic losses over the entire orbit. This should result in a strong suppression of nonthermal radiation of accelerated particles.
3. Discussion

The results presented above demonstrate the importance of hydrodynamics for the calculation of the high energy radiation of particles accelerated in the post-shock flow. Namely, (i) the adiabatic cooling time is significantly shorter than IC cooling time; (ii) the bulk Lorentz factor of the flow is rather large ($\gamma \sim 4$) already at distances, comparable to the size of the binary system. Both these effects have direct implication for interpretation of observations of high energy gamma- and X-ray emission components from the binary pulsar system PSR B1259-63/SS2883. In particular, the derived dependence in Eq. (4) (the ratio of IC cooling time to the nonradiative loss time as a function of the separation distance) implies that the HD simulations do not support (at least in the particular case of two isotropic winds colliding) the assumption of a sharp increase in the role of adiabatic losses towards periastron as hypothesized in ref. [17] for explanation of the observed deep in the gamma-ray light-curve of PSR B1259-63/SS2883 around periastron. On the other hand, the obtained absolute timescales of the adiabatic losses (compared to the Compton cooling times) show that the VHE signal should be significantly suppressed, especially at large separation distances. The HESS observation of PSR B1259-63/SS2883 [1] supports this conclusion: the signal from the source was detected only during epochs close to the periastron passage.

The effect of the flow bulk acceleration strongly modifies the relationship between the synchrotron X-ray and inverse Compton gamma-ray fluxes produced by the same population of relativistic electrons. Indeed, as long as the magnetic field is frozen in the plasma, its strength is determined by the structure of the flow and may significantly vary across the flow. The plasma bulk motion affects the IC radiation production as well, but in a different way. Namely, in the co-moving frame, where electrons are distributed isotropically, the target radiation field will be Doppler boosted. This implies that hydrodynamical effects can lead to a significant deviation from the standard relations between the X-ray and VHE gamma-ray fluxes (see e.g. [20, 21]).

Moreover, due to the large bulk Lorentz factors (for details see [19]), the observed fluxes should have strong orbital phase dependence. Indeed, the direction of the post shock flow varies with the motion of the pulsar along the orbit around the star. This implies significant changes of the Doppler factor $\delta$. Namely, $\delta \gg 1$ for small viewing angles (when the flow bulk velocity is directed towards the observer); and $\delta \ll 1$ for large viewing angles. Such a geometry is expected, in particular, at the periastron passage. Correspondingly, this will have a strong impact on the light-curve of nonthermal radiation of electrons, $F_\gamma \propto \delta^n$ where typically $n \geq 3$. Interestingly, in such a case one should expect a direct correlation between different energy bands (from radio to VHE), even though the electrons responsible for these energy intervals of electromagnetic radiation may not have the same origin. This conclusion is supported by multiwavelength observation of PSR B1259-63/SS2883 [14]. Moreover, this effect could be the reason for the deep in the VHE light-curve close to the periastron as reported by the HESS collaboration [1].

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