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Electron and positron acceleration in Pulsar Wind Nebulae

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Introduction

Pulsars release their spin-down power in the form of a relativistic electron-positron wind characterised by a large magnetisation parameter $\sigma \gg 1$ [1], defined as the ratio of the Poynting flux to the particle kinetic energy flux. When the wind impacts with the slowly moving surrounding environment, a reverse or termination shock (TS) forms, where the Poynting flux is dissipated. At this location, the energy is converted into kinetic energy of charged particles, mostly electrons and positrons, which emit inverse Compton (IC) and synchrotron radiation that is observed as a Pulsar Wind Nebula (PWN) downstream of the shock. These particles are likely to be accelerated to high energies via a Fermi-like process in which they gain energy by elastically scattering off electromagnetic waves both upstream and downstream and performing many shock crossings.

The process able to perform the energy conversion at TS remains uncertain, even though recently it has been suggested [2] that the propagation of superluminal waves upstream of the shock might trigger the dissipation of the Poynting flux through the formation of instabilities and small-scale shocks. Superluminal waves can be generated at the TS when the pulsar frequency exceeds the proper plasma frequency $\omega_{p0} = \sqrt{\frac{8\pi n e^2}{m}}$, where n is the density of the fluid and m is the electron mass. In this case the incoming fluid is slowed down and heated up until a precursor with turbulent electromagnetic fields is established ahead of the shock. Particles encountering the turbulence can be reflected into the upstream, forming a population of pre-accelerated particles which can be considered to have been injected into a subsequent Fermi-type process.

are injected in the true Fermi-type mechanism.

We address this problem in the context of γ-ray binaries, in which a pulsar orbits a massive main sequence star. In this case, the wind launched by the companion star compresses the pulsar wind and dictates the location of the TS [3], which in turn affects the density in the pulsar wind. During the resulting orbital modulation of the local plasma frequency, the condition $\omega > \omega_{p0}$ for the formation of the shock precursor can be fulfilled, triggering the particle acceleration.

In this contribution we investigate the role played by the onset of this electromagnetically

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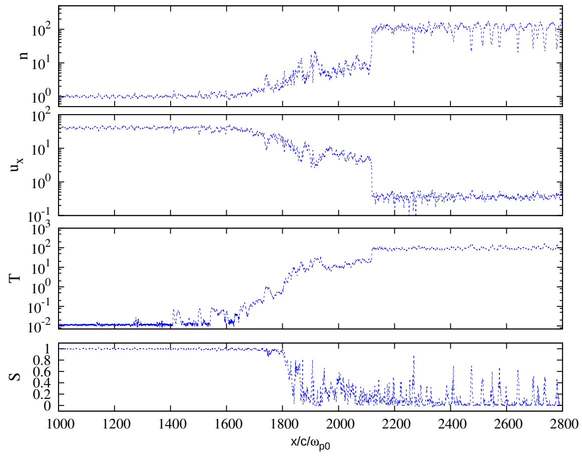

Figure 1: *From top to bottom: density, x component of the four velocity, temperature and normalised Poynting flux profiles of the plasma across the shock ($x_{sh} \sim 2120\, c/\omega_{p0}$) at $t = 2500/\omega_{p0}$. The interaction with the superluminal waves forms a precursor in the upstream where physical quantities smoothly vary before the sharp transition at the shock front.*

modified structure in the injection mechanism. The turbulent fields in the shock front are simulated with a 1-dimensional code and used to perform numerical integration of a large number of particle trajectories from which we determine the fraction of particles reflected at the shock, i.e. the fraction of particles which enters a Fermi acceleration process.

Method

We simulate the pulsar wind TS by mean of a 1-dimensional, relativistic, 2-fluid code supplemented by Maxwell's equations [2]. The pulsar striped-wind driven by the obliquely magnetised, rotating pulsar is treated in the upstream as a fully transverse, circularly polarised, sinusoidal magnetic shear (a "sheet-pinch") whose phase-averaged magnetic field is null. In the striped-wind model such a scenario is realised in the pulsar equatorial plane [4]. The initial conditions in the downstream are determined by the solution of the Rankine-Hugoniot relations, once the following parameters are provided: the Lorentz factor of the incoming fluid Γ_s, the magnetisation parameter σ and the frequency of the pulsar ω in units of the upstream proper plasma frequency ω_{p0}.

We use the background fields obtained with this set-up to numerically integrate trajectories of test particles (electrons and positrons) subject to the Lorentz force. We employ a form of the equations of motion which is suitable to avoid issues of momentum accumulation when only the magnetic field is present. The solution of our set of equations is advanced adopting a 4th order Runge-Kutta method with adaptive time step-size. To investigate whether this configuration of turbulent fields is able to inject particles in a Fermi-like acceleration process, we initiate the trajectories far upstream, with an isotropic distribution and almost at rest in the local fluid frame. We set two boundaries in the simulation box, one upstream and one downstream at distance L_{up} and L_{down} from the shock front respectively. Each trajectory is followed until it reaches the region between the boundaries and it then crosses either of the two. Particles registered at the upstream boundary, are labeled as reflected and contribute to the number of particles injected in

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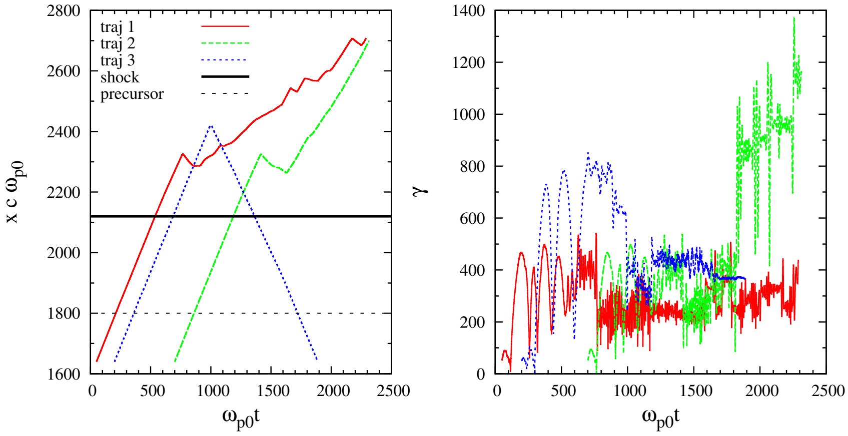

Figure 2: *Typical trajectories. Left panel: time evolution of the x coordinate of the motion. The solid black line represents the shock position and the dashed black line represents the approximate position of the border of the precursor in the steady state. Right panel: energy evolution of the corresponding particle.*

the acceleration process.

Results

We aimed to obtain a precursor which, after a first phase of expansion into the upstream, stabilises in a steady state for $\Delta t \gg 1/\omega_{p0} > 1/\omega$, namely comparable to, but still smaller than, the characteristic timescale of the orbit of the binary system. We obtain this configuration for $\Gamma_s = 40$, $\sigma = 10$ and $\omega = 1.2\omega_{p0}$. In Fig. 1 we show the profile of density, x component of the 4-velocity, temperature and Poynting flux of the plasma across the shock front at $t = 2500/\omega_{p0}$, when the stationary precursor has already established. For the chosen configuration, physical quantities like density and temperature form a region of smooth transition, which is the precursor created through the interaction with electromagnetic waves, before undergoing a sharp transition at the location of the shock ($x_{sh} \sim 2120\,c/\omega_{p0}$) as it happens for hydrodynamical shock fronts. In addition, we notice in the fourth panel of Fig. 1 that the Poynting flux starts decreasing at the border of the precursor $1800\,c/\omega_{p0}$ and it is almost completely dissipated downstream the shock, a part from some residual field fluctuations. With our initial conditions, after $\Delta t \sim 1200/\omega_{p0}$ the precursor stops expanding into the upstream, reaching a stationary state during which its spatial extension remains constant. This phase lasts $\Delta t \sim 1200/\omega_{p0}$ before the simulations is stopped. Periodic boundary conditions of this steady state are created to increase the time interval available for numerical integration. We tested whether this implementation affected the trajectories and we found that the choice of the number of folding and of the time extension of the periodic boundary does not affect spectra and angular distributions of particles registered on both upstream and downstream boundaries.

Because of the interaction of the "sheet-pinch" with the superluminal waves, the precursor

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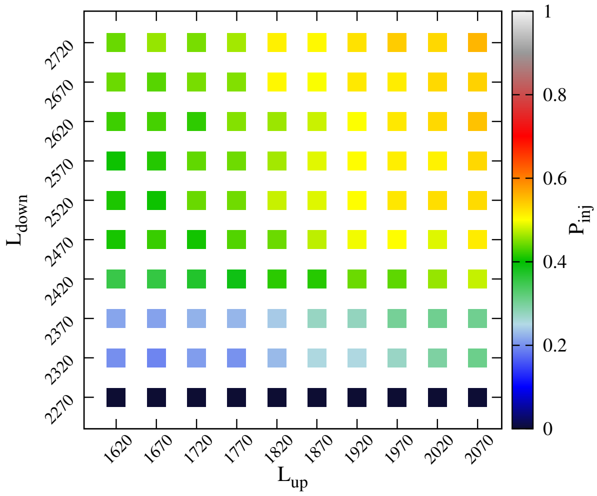

Figure 3: *Injection probability grid obtained counting the particles crossing the upstream boundary for different positions of the downstream and upstream boundaries.*

and the region immediately downstream the shock are characterised by turbulent fields which deflect and accelerate test particles. This is visible in Fig. 2, where the evolution of the x coordinate and of the corresponding energy are plotted as a function of time for a sample of characteristic trajectories. The fraction of particles injected in a true acceleration process is computed by counting how many trajectories cross the upstream boundary travelling against the flow. We compute this number for many positions of L_{up} at fixed position of L_{down} and repeat the procedure for many values of L_{down}, thus building a grid of values for the injection probability. This is plotted in Fig. 3, where we show that as the two boundaries recede from the shock, P_{inj} asymptotes to $\sim 40\%$. This value is large compared to that found for other relativistic shocks (e.g. $P_{inj} \sim 12\%$ for relativistic, oblique shocks [5]), suggesting that electromagnetically modified shocks are very effective in injecting particles in a Fermi mechanism.

Acknowledgements

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