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Are Gamma Ray Burst Driven by Gravitational Waves?

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Abstract. We investigate the non-linear interaction of a strong Gravitational Wave with the plasma during the collapse of a massive magnetized star to form a black hole, or during the merging of neutron star binaries (central engine). We found that under certain conditions this coupling may result in an efficient energy space diffusion of particles. We suggest that the atmosphere created around the central engine is filled with 3-D magnetic neutral sheets (magnetic nulls). We demonstrate that the passage of strong pulses of Gravitational Waves through the magnetic neutral sheets accelerates electrons to very high energies. We conclude that in several astrophysical events, gravitational pulses may accelerate the tail of the ambient plasma to very high energies and become the driver for many types of astrophysical bursts.

Key words: gravitational waves–compact objects:— GRBs.

1 Introduction

The interaction of Gravitational Waves (GW) with the plasma and/or the electromagnetic waves propagating inside the plasma, has been studied extensively (see Brodin and Marklund, 1999). All well known approaches for the study of the wave-plasma interaction have been used, namely the Vlasov-Maxwell equations (see Macedo and Nelson, 1982), the MHD equations (Papadopoulos and Esposito, 1981) and the non-linear evolution of charged particles interacting with a monochromatic (Varvoglis and Papadopoulos, 1992). The Vlasov-Maxwell equations and the MHD equations were mainly used to investigate the linear coupling of the GW with the normal modes of the ambient plasma, but the normal mode analysis is a valid approximation only when the GW is relatively weak and the orbits of the charged particles are assumed to remain close to the undisturbed ones. Several studies have also explored, using the weak turbulence theory, the non-linear wave-wave interaction of plasma waves with the GW.

In this article, we re-investigate the non-linear interaction of an electron with a GW inside a magnetic field, using the Hamiltonian formalism. Our study is applicable at the neighborhood of the central engine (collapsing massive magnetic star (Fryer et al., 2002)) or during the final stages of the merging of neutron star binaries (Shiabata and Uryu, 2002). We find that a strong but low frequency (10 KHz) GW can resonate with ambient electrons only in the neighborhood of magnetic neutral sheets and accelerates them to very high energies in milliseconds. Relativistic electrons travel along the magnetic field, escaping from the neutral sheet to the super strong magnetic field, and emitting synchrotron radiation. We propose that the passage of a GW through numerous localized neutral sheets will create spiky sources which collectively produce the highly variable in time Gamma-Ray-Bursts (GRB) observed (see van Paradijs et al, 2000 and references there-in).

2 Our model

The main points of the proposed model are

- We assume that a strong gravitational wave(GW) generated from the collapse of a massive magnetized star to form a black hole or during the merging of neutron star binaries(central engine).
- We suggest that the atmosphere created around the central engine is filled with 3-D magnetic neutral sheets (magnetic nulls).
- Strong pulses of Gravitational Waves passage through the magnetic neutral sheets accelerating electrons to very high energies.
- Superposition of many such short lived accelerators, embedded inside a turbulent plasma, may be the source for the observed Gamma-Ray and/or X-Ray Bursts.

3 GW as particle accelerator

We will establish the mathematical tool to discuss the above scenario:

The motion of a charged particle in a curved space and in the presence of a magnetic field is described by a Hamiltonian, which, in a system of units $m = c = G = 1$, is given by the Hamiltonian $H(x^\alpha, p_\alpha) = \frac{1}{2} g^{\mu\nu}(p_\mu - eA_\mu)(p_\nu - eA_\nu) = \frac{1}{2}$ where $g^{\mu\nu} = \eta^{\mu\nu} + h^{\mu\nu}$ with $|h^{\mu\nu}| \ll 1$, p_α are the generalized momenta corresponding to the coordinates x^α, A_μ is the vector potential, and e is the charge of the particle with mass $m = 1$.

We assume that $\vec{B} = B_0 \vec{e}_3$, with $B_0 = const.$, the GW has the form, $h \sim \alpha \exp(\psi), \psi = k_\mu x^\mu = \nu(\sin\theta x^1 + \cos\theta x^3 - x^0)$, $\nu = \omega/\Omega$, $\Omega = eB_0 = 1$(Larmor frequency); α is the amplitude of the GW propagating in a direction $\vec{k}$ of angle θ with respect to the magnetic field. We find that for small values of a, the particle is traped in the main resonance of the wave particle interaction and is not accelerated. Increasing further the perturbation parameter a, the width of the resonances increases and the chaotic motions start to dominate the interaction. When the amplitude a exceeds a critical value a_c, overlapping of resonances takes place and large chaotic regions are generated (Varvoglis and Papadopoulos, 1992). The evolution of the particles changes character when the direction of propagation of the GW is almost parallel to $\vec{B}$. In this case, chaos disappears, and the particles undergo large energy oscillations. We verify that Chaotic diffusion is possible for $a \geq a_c$ and for the particles with $\gamma \geq \gamma_c$.

We follow the evolution of 3×10^4 particles forming initially a cold energy distribution $N(\gamma, t = 0) \sim \delta(\gamma - 3)$, where δ is the Dirac delta function i.e. all particles have the same initial energy $\gamma = 3$. A large spread in their energy is achieved in short time scales, and for $t = 1000$, a non-thermal tail extending up to $\gamma = 100$ is formed. We repeat the same analysis, assuming that the evolution of the tail of a Maxwellian distribution. Furthermore we deal with the mean energy diffusion in time and found that the follow a simple scaling law $< \gamma > \sim t^d$

Our main findings from the study of an ensemble of particle with the Gravitational wave are: (1) The GW can accelerate electrons from the tail of the ambient velocity distribution to very high energies provided that (2) ($\gamma > 10 - 100$), $0.005 < \alpha < 0.5$ and $5 \leq \omega/\Omega \leq 20$. The acceleration time depends in general on α but is relatively short msecs at the distance 10^8 cm, (3) The mean energy diffusion of the electrons interacting with the GW follows in time a simple scaling $< \gamma > \sim t^d$, where $d \sim 0.5$.Let us now assume that the null sheets have a distribution $N(l) \sim l^{-b}$. and the acceleration time is $t_{acc} \sim l_{acc}/c$. Then $N(t) \sim t^{-b}$. We also know that $< \gamma > \sim t^d$. Because of the relation $N(\gamma)d\gamma = N(t)dt$ we end up with a relation $N(\gamma) \sim \gamma^{(1-b-d)/d}$.We verify that for $b = 3/2$ and $d = 0.5$, $N(\gamma) \sim \gamma^{-2}$. The obtained result agrees with the observed spectrum of the synchrotron distribution which has also a power law dependence in energy, namely $N(\gamma) \sim \gamma^{-\varepsilon}$ were $\varepsilon \simeq 1.8 - 2.0$ The energy transferred from the GW to the high energy particles by passing through **one neutral sheet** is $E_{ns} \sim \left(\frac{n_t}{n_0}\right) n_0(\ell_{acc}^2 \times \Delta\ell) \times \gamma mc^2$ where n_0 is the electrons density, n_t are the electron at the tail of the local Maxwellian, $\Delta\ell$ is the thickness of the magnetic neutral sheet. The total number of magnetic neutral sheets expected to interact with the GW is $f(\Delta L)^3$, where f is the filling factor of neutral sheets inside the atmosphere of the central engine. The total energy transferred to the GRB is $W_{tot} \sim \left[f \frac{(\Delta L)^3}{(\ell_{acc}^2 \times \Delta\ell)}\right] \times \left(\frac{n_t}{n_0} n_0(\ell_{acc}^2 \times \Delta\ell) \times \gamma mc^2\right)$. Using typical numbers, $n_0 = 10^{12}$ cm$^{-3}, n_t/n_0 \sim 10^{-1}, \gamma = 100, \ell_{acc} \sim 10^8$ cm$, \Delta\ell \sim 10^7$ cm $f \sim 10^{-1}$ and assuming that the burst duration is 1s which implies that $\Delta L \sim 3 \times 10^{13}$ cm, the total energy estimated is approximately 10^{47}-10^{48} ergs. We then conclude that (1) The passage of a GW through a turbulent magnetized plasma can accelerate sporadically electrons(short msec spikes). (2) The energetic and the spectrum of the accelerated particles seems to agree with the existing data provided that the null sheets have a distribution of characteristic lengths, (3) The total energy of the burst expected from the above interaction is close to 10^{48} ergs.

Returning to our initial question: Can the GW drive the GRB? We propose that it is not possible to drive the most intense GRB bursts bursts observed but it may play a crucial role for the weak GRB bursts and the strong X-ray bursts recently observed. We the conclude that in several astrophysical events, gravitational pulses passing through a turbulent magnetized plasma may accelerate the tail of the ambient velocity distribution to very high energies and become the driver for many types of astrophysical bursts.

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