Gravitational-to-Electromagnetic Waves Conversion and Gamma-Ray Bursts Calorimetry: The GRB980425/SN1998bw $\sim 10^{49}$erg Radio Emission

Herman J. Mosquera Cuesta[1,2]
[1] *Centro Brasileiro de Pesquisas Físicas, Laboratório de Cosmologia e Física Experimental de Altas Energias*
Rua Dr. Xavier Sigaud 150, CEP 22290-180 Urca, Rio de Janeiro, RJ, Brazil
[2] *Centro Latinoamericano de Física (CLAF), Avenida Wenceslau Braz 173, Botafogo, Rio de Janeiro, RJ, Brazil*

(October 23, 2001)

The unusual features of supernova (SN) 1998bw and its apparent association with the gamma-ray burst (GRB) event GRB980425 were highlighted by Kulkarni et al. [1,2]. At its peak SN1998bw was anomalously[1] superluminous in radio wavelengths with an inferred fluence: $E_{radio} \geq 10^{49}$erg [Kulkarni, S., et al., Nat. 395, 663 (1998)], while the apparent expansion velocity of its ejecta ($\sim 10^{-5}$M$_\odot$) suggests a shock wave moving relativistically ($V_{exp} \sim 2c$). The SN1998bw unique properties strengthen the case for it to be linked with GRB980425. I present a consistent, novel mechanism to explain the peculiar event SN1998bw and similar phenomena in GRBs: Conversion of powerful, high frequency ($\sim$ 2kHz) gravitational waves (GWs) into electromagnetic waves (EMWs) [3–7] might have taken place during SN1998bw. Yet, conversion of GRB photons into GWs, as advanced in Johnston, Ruffini and Zerilli [Phys. Lett 49B, 185 (1974)], may also occur. These processes can produce GRBs depleted in γ-rays but enhanced in x-rays, for instance, or even more plausible to induce *dark* GRB, those with no optical afterglow. The class of GWs needed to drive these gamma-ray bursts' calorimetric changes may be generated by: a) the non-axisymmetric dynamics of a torus surrounding the hypernova (or failed supernova) magnetized stellar-mass black hole (BH) remnant, as in the van Putten's mechanism for driving long GRBs powered by the BH spin-energy [Phys. Rev. Lett. 87, 091101 (2001) [8], or in Van Putten and Ostriker [Astrophys. J. 552, L32 (2001)] mechanism for accounting for the bi-modal distribution in durations in GRBs, where the torus magneto-hydrodynamics may be dominated by either hyper-accretion on to a slowly spinning BH or suspended accretion on to a fast rotating BH. b) the just formed black hole with eletromagnetic structure (EMBH); as in the Ruffini et al. GRBs central engine mechanism [Astrophys. J. 555, L107 (2001); Astrophys. J. 555, L113 (2001)] [9], provided the issue concerning the origin of the black hole charge be suitably clarified. In both of these mechanisms the total energy radiated as GWs is about $\Delta \mathrm{E}_{\mathrm{GW}_s} \sim 10^{53}\mathrm{erg}(\frac{\mathrm{M}}{10\mathrm{M}_\odot})$, which for the conversion efficiency estimated here turns out to be enough to explain the superluminous radio wavelength emission from SN1998bw. Thus, I argue this process could have induced the enhancement in the radio-luminosity of SN1998bw as evidenced in its light curve (Figure 2 in Ref. [1]), and optical light curve of GRB980326 [Bloom et al., Nature 401, 453 (1998)] and GRB990712 [Björnsson et al., Astrophys. J. 552, L121 (2001)]. Moreover, GWs-driven plasma density perturbations moving at the speed of light may up(or down)-convert fireball photons [10], which could render further substancial modifications of the gamma-ray burst/supernovae calorimetry.

PACS: 04.70.-s, 97.60.Lf, 04.30.Db, 98.70.Rz, 41.20.Jb, 52.35.H

I. ASTROPHYSICAL MOTIVATION

Cosmological GRBs release energy approaching the rest-mass of a neutron star on a timescale of a few seconds. The leading popular models for GRBs are coalescences of compact binaries and collapses of massive stars. For the latter picture it becomes unescapable that a bright supernova (SN) should come along with the GRB, which is expected to leave a BH as its remnant. It is arguable that the SN emission may compete with the much brighter afterglow generated by the relativistic blast wave triggering the GRB itself. Therefore, the strongest evidence of the GRB massive star origin would be to observe a SN coincident with a GRB. Several claims in this direction have been put forward: GRB980326 [11], GRB980425 (SN1998bw) [1] and GRB990712 [12]. below we exploits these events as prototypes of most GRBs as observed by BATSE.

Most descriptions of GRBs involve catastrophic phenomena at cosmic scale distances in which the GRB source itself is "destroyed" at the onset of the outburst. Coalescing binary neutron stars, neutron star black hole binaries, dyadospheric black holes, and at least some supernovae (Hypernovae, Collapsars) explosions are among these candidates for hosting the intriguing bursts' central engine. The GRBs leading scenario, the fireball model [13–15] has successfully explained what is going on in the cosmological sources of GRBs and in their afterglows (Ref. [14,16–19], and references therein). A fireball, a huge concentration of radiation plus an opaque electron-positron plasma, released in a small space, is the analogous of a supernova, in which its ejecta, a relativistic blast wave of Lorentz factor $LF \sim 10^4$, is supposed to trigger the γ-surge. It carries too much an energy that powering bursts observable from the Hubble distance is not so a difficult task.

A. Anomalous GRBs light curves

In the star field around GRB980425, Galama et al. [2] discovered an unknown bright optical object lying at the western spiral-arm of the galaxy ESO184-G82, and suggested that source could be a GRB980425 parental supernova. Spectroscopic observations and their interpretation [20] confirmed SN1998bw to be a Type-Ib/c peculiar supernova located at $z = 0.0083$, i.e., 38 MPc. The SN1998bw radio curve exhibits a rapid early rise within ±2 days after the time of GRB980425, what further reinforces the possible association. Its peak spectral radio-luminosity:

$$L_{SN}^{Radio} \sim 4\pi S_6 d^2 \sim 8 \times 10^{28} \mathrm{ergs}^{-1}\mathrm{Hz}^{-1}, \quad (1)$$

for $d \sim 38$Mpc, was larger than for typical Type-II supernovae (e.g., SN1998Z). Its angular radius, which about 10 days after the explosion was $\theta_s \sim 9\mu$as [1], was expanding at a velocity of $\geq 9 \times 10^4$km s^{-1}.

In modeling the radio emission from SN1998bw Kulkarni et al. [1] realized that something went wrong with their estimate of the brightness temperature by using an *incoherent synchrotron model* for the radio emission from SN1998bw. The resulting temperature: $T_{icc} \leq 5 \times 10^{11}$ K, is quite low when compared to the inferred brightness

$$T_B = 2 \times 10^{13} \mathrm{S(mJy)}(\lambda/6\mathrm{cm})^2 \nu_{60}^{-2} t_d^{-2} d_{38}^2. \quad (2)$$

Here S is the flux at wavelength λ (see Ref. [1] for further details and definitions). Then, they attempted to match their model light curve brightness temperature to the one derived from the observations by considering the overall *energetics* of the event, and a radio emitting shock moving much faster than the one producing the optical emission. However, this procedure only works for explaining the first peak in the light curve, it cannot account for the second one occurred near 30 days after the rise [1]. Below I introduce an inedit mechanism to explain these unusual features of SN1998bw, including a potential explanation for the occurrence of this hump (second peak) in its light curve. An analogous physics should play a role in other GRB events.

In the same lines, nearly one month earlier than GRB9890425/SN1998bw another prospective association between GRBs and SNe was observed: GRB980326 [11]. Optical observations of GRB980326 evidenced an also unusual light curve [11]. The transient brightened about 3 weeks after the burst, with a flux sixty times larger that the one extrapolated from the rapid decay seen at early time [11]. The GRB980326 spectrum changed very dramatically turning itself extraordinarily red quite early. The GRB980326 R-band photometry exhibited a characteristic power law decay in the flux temporal evolution followed by an apparent flattening. The standard interpretation leads to argue that the decaying flux is the afterglow emission, while the constant flux indicates the presence of the GRB980326 host galaxy, a view that earlier observations had confirmed [11]. But surprisingly, Bloom et al. late observations [11], about nine months later than the GRB980326 event, promoted no galaxy at the position of the burst optical transient, implying that at most $R \sim 27$ could be a plausible magnitude for this presumed host galaxy. Because of all this peculiar phenomenology it was argued by Bloom et al. [11] that the new source is an underlying supernova. Their interpretation then suggested this event as the first evidence for a GRBs/SNE connection.

This sort of phenomenological association GRBs/SNE also comes out from the re-examination of the optical afterglow of GRB990712 by Björnsson et al. [12]. It was shown that a break in the light curve indeed appears to be present in the V-band about 1-2 days after the GRB990712 event. Such re-analysis clearly confirmed a prediction based on the study of polarization data, and showed evidences for a collimated outflow with moderate spreading $\theta \sim 6^o$. Thence, a prominent supernova-like component is visible in the post-break light curve which is also clearly observed in the R-band, a spectral region where no signs of such a break is expected. The interpreation is that the data provide a tantalizing case for the GRB/SNe association in this event too.

From the above phenomenology one is enabled to speculate on the possible conversion of GWs into EMWs, and viceversa, during GRBs, as a possible explanation of these anomalies. A strong case for this possibility is presented in the next sections. The paper is organized as follows: Section II discussed theoretical arguments for the graviton-photon interconversion. Section III focus on the most prospective mechanisms for the generation of GWs during GRBs events. We review sources where the central engine is both a compact (most likely a stellar-mass BH) and strongly magnetized object, as in van Putten's GWs from a torus orbiting a BH; and Ruffini et al.'s mechanism involving a dyadospheric BH, an EMBH. In Section IV the efficiency of the GWs-EMWs conversion process is estimated. The result is used to compute the augment in the radio emission from GRBs/SNe associations. Section V exploits the possibility of GWs-plasma coupling in the conversion region around the BH to raise or drop the initial frequency of incident GWs in the context of this mechanism. Some conclusions and potential directions are presented in Section VI.

II. RADIOWAVES DUE TO GRAVITATIONAL WAVES

Several authors have considered the possible coupling between GWs and EMWs, including theoretical approches [3,10,6,21,7] and astrophysical applications [10,4,5]. This process is fundamented on the Equivalence Principle which General Relativity is based on. Recently, Marklund, Brodin and Dunsby [6] have demonstrated that conversion of gravitational waves into electromagnetic waves in a background, static homogeneous electromagnetic field may occur. In the same lines, it was shown by Moortgat, 't Hooft and Kuijpers [7] that the phenomenon could be relevant for gamma-ray bursts, even without photon acceleration, i.e., frequency enhancement (or decreasing) induced by GWs driven density gradients [10].

In this Article I suggest that the graviton-photon conversion mechanism may explain, without any fine tunning, the energy excess in the electromagnetic light curve of very energetic phenomena such as SN explosion and/or GRB events, in particular their anomalous (extraluminous or subluminous) light curves. Although the EMWs emission due to GWs is not a new idea, the very innovative concept I present here concerns the possibility of GWs-EMWs conversion to be responsible for not only the great enhancement in both the SN1998bw radio [1] and visible light luminosities [22], but also its subluminosity in γ-rays and x-rays [1]. It also applies to the enhancement in the GRB980326 and GRB990712 optical emission [11]. If proved efficient, the mechanism invoked could come into play to help to provide a better understanding of the calorimetry of the most luminous GRBs ever detected [23,24], and it would also innaugurate a new perspective in detection of gravitational waves. I stress that the idea here presented is the by-product of the interplay of several pieces of physics and astrophysics of current acceptance among researchers of those fields.

A. Constraints on conversion environments

The expected optimal astrophysical environments for this process to take place should satisfy the following requirements: a) to produce GWs carrying large amounts of energy, so that even for a small conversion efficiency into EMWs the outcome will be still significant. b) to emit GWs of relatively very high frequencies, i.e., $\sim$ 10kHz, otherwise the EMWs (with the same GWs frequency) will be absorbed in its journey through the interstellar plasma (IP), due to its frequency going down the IP one. c) The interaction must take place in extremely strong magnetic fields, and d) the interaction region must be vacuum or a thin diluted plasma, to neglect effects coming from the difference in the dispersion relation of vacuum EMWs and GWs dissipations.

I argue here that all the quoted requirements are satisfied by the conditions existing after a SN collapse and envelope ejection. The formation of the stellar-mass remnant BH may create a rarified thin plasma, a region almost baryon depleted, where the strength of the magnetic field (dipole in nature, see Figure 1 in van Putten's 2001 Letter [8]) could transiently achieve supercritical values over a timescale relatively long, compared with the period of the GWs emitted, so as to drive the long GRBs [8,25]. The region that could satisfy these requirements could be the space inner to the torus and outside the BH horizon. The characteristic size of this region is about 50km, a distance scale which is inferred from the stability condition of the torus orbiting the BH. This typical length scale essentially corresponds to the inner GWs radiation zone, the region where most of the GWs-EMWs conversion is expected to take place [6,21,7]. Note, however, that according to Marklund et al. [6] the effective size of the GWs-EMWs transmitter is determined by either the extension of the (static) magnetic field or the mismatch distance $L \equiv \frac{2k}{\pi(\Delta k)^2}$, whichever is smaller (here k is the EM wavenumber). This is due to the fact that the GWs and the extraordinary EMW mode satisfy nearly the same dispersion relation in the regime where $\omega_p^2/\omega_c << \omega \lesssim \omega_p << \omega_c$ (see discussion in Section V-A), what tends to make the linear wave interaction coherent over large distances, i.e., of the order of $L_{coup} \gtrsim 60 R_{BH} \sim 1200$km (see Section IV-A, below). The overall magnetic field in the torus is expected to be inheritaged from the remnant flux of the GRB progenitor star [8]. This manner, I suggest, is possible to obtain a large enhancement in the total EMWs luminosity, a high conversion efficiency; to say, which is enough to explain the unusual calorimetry of cosmological GRBs, as evidenced in particular by the radio emission from SN1998bw [1] and the optical light curve of both GRB980326 [11] and 990712 [12].

III. HIGH POWER AND FREQUENCY GWS FROM A TORUS ORBITING A BH

Although over this Section we shall discuss the mechanism for generating GWs during long GRBs suggested by van Putten [8], the attent reader should be aware of the fact that essentially the same physics must outcome if one uses the Ruffini et al. [26] dyadospheric BH engine mechanism for GRBs, or any other mechanism able to produce GWs with the deserved characteristics: energy and time scale, as already highlighted.

Hypernovae and collapsars are the main theories available to account for the GRBs. In these models, the explosion of a massive star leaves a BH remnant which may be encircled by a massive, dense accretion disk, a torus to say, formed from the supernova fallback material. It has been argued by van Putten [8,27] that a large amount of gravitational radiation from the orbiting torus can be powered by the BH spin-energy due to the magneto-hydrodynamical (MHD) coupling in the system. Next we follow van Putten's [8,27] main lines to the estimates of the GWs energetics from the stressed torus. In this mechanism the torus is coupled to the spin-energy of the BH through its magnetosphere; in analogous way as in pulsars. The MHD coupling, through Maxwell stresses, drives non-symmetric instabilities and lumpiness in the torus. The torque,

$$T_{BH} = (\Omega_{BH} - \Omega_{torus}) f_{BH}^2 A^2 \equiv -\frac{dJ_{BH}}{dt}, \tag{3}$$

applied by the BH, of equilibrium magnetic moment $\mu_{BH} \simeq aB_\theta J_{BH}$, compensates for the angular momentum losses in magnetic winds and radiation (even neutrinos) from the torus. In this equation Ω_{BH} and Ω_{torus}, define the BH and torus angular velocities, respectively, J_{BH} the BH angular momentum, and $2\pi f_{BH} A$ denotes the flux in interconnecting magnetic field lines, with $f_{BH} \propto (\frac{M_{BH}}{a})^2$ the fraction of the torus magnetic flux incident on the BH, and $2\pi A = 2\pi ab < B_\theta >$ the net magnetic flux released from the torus, with a and b the torus principal semi-axes, and $< B_\theta >$ the mean poloidal magnetic field. This interaction prevents subsequent inflow of disk material, thus enabling the occurrence of a state of *suspended accretion* around a rapidly rotating BH. This state is expected to survive for longer [8], at least over the BH spin-down time. Since the stresses drive the matter distribution in the torus quadrupolar, then it should emit GWs. For a thorough discussion on the MHD physics in this system the reader is addressed to the complete review by van Putten [Phys. Rep. 345, 1 (2001)] [28].

A. GWs from suspended accretion around BHs

As pointed out above the main source of GWs in this picture is the anisotropic torus itself in suspended accretion, that is, in a dynamical configuration where: $\Omega_{BH}/\Omega_{torus} >> 1$. We can estimate the total gravitational and electromagnetic (E-M) radiations from a torus of ellipticity ϵ, mass M_{torus}, and magnetic moment μ_{torus}, spinning around its center of mass, by recalling that its quadrupole magnetic and mass moments read

$$Q_{torus}^{mass} = \epsilon M_{torus}, \qquad Q_{torus}^{EM} = \epsilon \mu_{torus}. \tag{4}$$

These relations lead to GWs and EMWs luminosities given as

$$L_{torus}^{GWs} = \frac{32G}{5c^5} \left(\Omega_{torus} M_{BH}\right)^{10/3} \left[\frac{M_{torus}}{M_{BH}}\right]^2 \epsilon^2, \tag{5}$$

$$L_{torus}^{EMWs} = \frac{\epsilon^2}{\pi} \left[\Omega_{torus} M_{BH}\right]^4 \left(\mu_{torus} M_{BH}^2\right)^2. \tag{6}$$

It has been shown that only in the presence of magnetic fields unable to provide pressure enough to counterbalance the source gravitational energy density (B fields gravitationally weak, in the use of Ref. [8]), the ratio between $L_{torus}^{GWs}/L_{torus}^{EMWs}$ is larger than 1 [8]. However, as is argued in the next Section (IV-B), this could not be the case if the remnant magnetic field in the torus is rather large. Physical arguments and references in support of this possibility are given there. In such a case, the radio contribution to the calorimetry of GRBs could be dominant so as to appear clearly in the particular light curve of SN1998bw as a noticeable radio luminosity enhancement.

B. GWs characteristics

The orbital revolution timescale of the torus can be inferred from its characteristic radius: $< R_{torus} > \sim M_{BH}^{7/5} \Omega_{BH}^{2/5} \sim 50$km [8,27]) and the orbital velocity of a stably orbiting accretion disk at that distance from the BH of fiducial mass $7M_\odot$: $V_{torus} \sim c/3$. This way we obtain

$$\Delta T_{orb} \equiv \frac{< R_{torus} >}{V_{orb}} \sim [1 \times 10^{-3} - 5 \times 10^{-4}]\ \mathrm{s}. \tag{7}$$

Although the GWs frequency undergoes a constant chirp. i. e., $df_{GWs}/dt =$ Constant., this timescale determines the frequency of the GWs emitted during the orbital evolution of the torus lumpiness as

$$f_{GW} \equiv 2 \times (\Delta T_{orb})^{-1} = [2 - 4]\mathrm{kHz}. \tag{8}$$

The GWs luminosity, $L_{\rm GWs}$, as a function of the BH luminosity, L_{BH}, can be obtained from the equilibirum conditions for the torque and energy in the suspended accretion state (see details in Ref. [8,27]). Since an equivalence in poloidal topology to a pulsar magnetosphere indicates that a large amount of the BH luminosity incides onto the magnetized material compressing the torus, that is; when most of the magnetic field on the horizon is anchored to the surrounding matter, then the total luminosity at the BH horizon can be estimated as

$$L_{BH} \simeq \mathrm{L}_{torus} = \Omega_{torus} (\Omega_{BH} - \Omega_{torus}) f_{torus}^2 A_{BH}^2. \tag{9}$$

From the BH-Torus MHD interaction we can derive a conservative estimate of the ratio between the BH spin frequency and the torus angular frequency as

$$\frac{\Omega_{torus}}{\Omega_{BH}} \sim 0.1. \tag{10}$$

Thence, the GWs luminosity can be recast as

$$L_{GWs} \simeq \Omega^2_{torus} A^2_{torus} \simeq L_{BH}/3. \tag{11}$$

Because the spin energy available from a maximally rotating BH is

$$\Delta E_{BH} \sim 4 \times 10^{53} \left(\frac{M_{BH}}{7M_\odot}\right) \mathrm{erg}, \tag{12}$$

then from Eq.(11) it follows that the energy to be released in GWs can be quantified as

$$\Delta E_{GWs} \sim 10^{53} \left(\frac{M_{BH}}{7M_\odot}\right) \mathrm{erg}. \tag{13}$$

Finally, from Eq.(13) we arrive to the effective GWs amplitude

$$h_{eff} \sim \left[\frac{M_{BH}}{D}\right] \left(\frac{\Delta E_{GWs}}{M_{BH}}\right)^{1/2}. \tag{14}$$

This relation produces $h_{eff} \sim 10^{-21}$ for a GRB event at a distance of ∼100 Mpc. It was shown in Ref. [8], that a GWs signal such as this could be detected by LIGO-I, VIRGO, and GEO-600 interferometers, what in passing turns long GRBs a prospective target for GWs detection.

IV. GWS-EMWS CONVERSION AND EFFICIENCY

A. GWs-EMWs dynamics

Since the gravitational and electromagnetic interactions are time-symmetric, satisfy the same dispersion relation and scale linearly, then they can resonate and transfer energy and momentum, i.e., the equivalent principle holds. This idea was originally discussed by Ruffini in the early 1970's [3], and very recently in Refs. [4–7]. Thus it is possible to estimate the efficiency in the EMWs-GWs conversion process by solving the linearized field equations for the *resonant term* of the z-axis outcoming E-M field with wavevector $|\vec{\kappa}| = \kappa_z = \omega/c$, from which the GWs will be produced. It is assumed that no absorption or scattering occurs, i.e., $b(z) = b$ (see below). This is the term that produces the oscillating source term for the GWs in the Einstein equations. It is an interference term proportional to the external (background) magnetic field $F^{(0)\mu\alpha}$. Such a term is the only relevant part of the stress-energy tensor of plane EMWs with amplitudes normalized to the GWs total energy density: $T^{\rm GWs}_{\mu\nu} = \frac{c^4}{16\pi G} < h^{TT}_{ij,\mu} h^{TT}_{ij,\nu} >$. From Einstein equations, thus we get the wave equation [7]

$$\begin{aligned}\Box\phi^\mu_\nu &= \frac{-8G}{c^4}\left(F^{(0)\mu\alpha}F_{\nu\alpha} - \frac{1}{4}\eta^\mu_\nu F^{(0)\alpha\beta}F_{\alpha\beta}\right)\\ &= -\frac{8G}{c^4}F^{(0)\mu\alpha}F_{\nu\alpha}.\end{aligned} \tag{15}$$

where

$$F^{(0)\mu\alpha}F_{\mu\alpha} \propto (E \cdot E^{(0)} - B \cdot B^{(0)}). \tag{16}$$

As stated just above, the GWs energy density reads

$$T^{00}_{GW} \sim \frac{c^4}{16\pi G} < (h_{\mu\nu,0})^2 > = \frac{c^4}{16\pi G} < \phi_{\mu\nu,0} >^2, \tag{17}$$

with the metric being given as

$$\phi^{\mu\nu} = \mathcal{R}\left[a(x)\left(\frac{16\pi G}{c^4\kappa^2}\right)^{1/2} \varsigma^{\mu\nu} e^{i\kappa_\alpha x^\alpha}\right], \tag{18}$$

where $\varsigma^{\mu\nu}\varsigma_{\mu\nu} = 1$, and $\varsigma^\mu_\nu = 0$. The electromagnetic (E-M) energy density (the Poynting flux)

$$T^{00}_{E-M} = \frac{1}{4\pi}(E^2 + B^2), \tag{19}$$

where the E-M field is given as

$$F_{\mu\nu} = \mathcal{R}\left[b(4\pi)^{1/2} f_{\mu\nu} e^{i\kappa_\alpha x^\alpha}\right]. \tag{20}$$

Here $f^{0\nu}f_{0\nu} = 1$, and $f^{ij}f_{ij} = 1$, and $\kappa^\alpha(GW) = \kappa^\alpha(EMW)$.

In a particular reference frame where: $E^{(0)} = 0$, and $B \perp B^{(0)}$, an by neglecting quadratic terms in d/dx and considering slowly varying amplitudes we get the field equation

$$\begin{aligned}\Box\phi^\mu_\nu = \left(\frac{16\pi G}{c^4\kappa^2}\right)^{1/2} \frac{\varsigma^\mu_\nu}{\kappa_x}\left(\kappa_\alpha\kappa^\alpha + \frac{d^2a(x)}{dx^2} + \right.\\ \left. +\ 2i\kappa_x\frac{da(x)}{dx}\right) e^{i\kappa_\beta x^\beta} = -\frac{16\sqrt{\pi}bG}{c^4}F^{(0)\mu\alpha}f_{\nu\alpha}e^{i\kappa_\beta x^\beta}.\end{aligned} \tag{21}$$

The resulting differential equation (21) can be solved for $a(z)$ to get a relation for the 'conversion factors' $a(z)$ e b as

$$\left|\frac{a(z)}{b}\right| = i\sqrt{\frac{4G}{c^4}} f_{\nu\alpha}\varsigma^\nu_\mu \int_0^z F^{(0)\mu\alpha}(z')dz' + a(0). \tag{22}$$

Next we use this result to define and compute the efficiency of conversion of GWs into EMWs.

B. Conversion efficiency and SN1998bw radio power

It turns out that from the supernova phenomenology we are considering here, and assuming no-incoming GWs: $a(0) = 0$ in Eq.(22), the efficiency of GWs-EMWs conversion may be computed from Eq.(22) as [7]

$$\begin{aligned}\eta \equiv \left|\frac{a(x)}{b}\right|^2 &= \frac{4G}{c^4}F^{(0)2}L^2_{coup}\\ &= 5 \times 10^{-4}\left[\frac{B_0}{10^{18}\mathrm{G}}\right]^2\left[\frac{L_{coup}}{10^3\mathrm{km}}\right]^2,\end{aligned} \tag{23}$$

with L_{coup} being the characteristic length scale of (coherent) interaction and $F^{(0)} = B_0$ the magnetic field strength inside the region of conversion.

In deriving this result we have considered that the characteristic (coherent) length scale of the GWs-EMWs interaction is $L_{coup} \sim 10^3$km -namely, the region III in Refs. [7,6]. This distance scale for conversion to occur is defined as the interaction radius, R_{int}, which is roughly equivalent to about (3-4) times the GWs wavelength: $\lambda_{\rm GWs} \equiv c \times \Delta T_{osc} \sim 300$km. We have also considered that the magnetic field (if of dipole nature) in the BH surroundings ($\sim [10^2 - 10^3]$km from the BH horizon) could transiently be as high as $F^{(0)} = B_0 = 10^{18}$G. Arguments in support of this choice are based on the fact, as discussed below, that the local magnetic field, B_0, in the plasma region where the GWs-EMWs is supposed to take place can transiently be amplified driven by the density perturbations induced by the GWs passing through. It is stressed in addition that magneto-hydrodynamical turbulence and mixing (as pointed out by van Putten [8]) may also occur. Such effects are also well-known to drive entanglement of pre-existent (the SN core remnant) magnetic fields, which may potentially be amplified to the values quoted here during the transient over which the GRBs and GWs are emitted and radio conversion process develops.

At this point a word of caution must be put forward: The Van Putten mechanism for GRBs stands on the existing of "gravitationally weak magnetic fields" in the region defining the BH-torus system, while our proposal works in a regime where the magnetic field strength is high enough so as to compete with the energy density of the central BH. The BH-torus system pervaded by a superstrong magnetic field is an "ill-understood" limit that still deserves a more detailed analisys. Nonetheless, we stress that such a huge magnetic field develops in a *low density* region *well outside* the central BH-torus system. It is unclear yet if its back-reaction can decidedly affect the BH-torus system dynamics till the point to raise questions about our results [†].

In fact, magnetic fields of $\sim 10^{15} - 10^{16}$G have been inferred to exist in accretion disks in active galactic nuclei where collimated bipolar jets and acceleration of ultra high energy particles (protons, for instance) is observed to occur. In the latter case is highly plausible that an analogous phenomenology develops in stellar-mass BHs torii, like in mini-quasars. Finally, recent studies suggest that $B^{SN}_{core} \sim 10^{20-21}$G [30–34] can exist in the interiors of newly born NSs having ferromagnetic or deconfined quark cores ($R_{core} \sim 5$km), where neutron motion is quantized. Assuming that the formation of a NS core-like structure preceeds the BH formation, it follows that the conjectured B-field in Eq.(23) is not so unlikely to transiently exist around the remnant torus. Thence $B \sim 10^{18-17}$G can certainly permeate the interaction region on this basis [‡]. Finally, a closing remark concerning the conversion efficiency itself: There exists the theoretical prediction by Johnston, Ruffini and Zerilli [21] that the conversion efficiency could be as high as some percentage of the total GWs energy produced in the process, instead of the several orders of magnitude smaller as shown here. If this high efficiency conversion can be achieved somehow, then it follows that more dramatic changes could be induced in the GRBs overall calorimetry through the process invoked in this paper. This more intriguing issue deserves a more careful reconsideration.

Consequently, by using Eq.(13) the

[†] Relevant to the last discussions is to quote that the extreme regime, in which a rapidly rotating electrically charged BH is immersed in a magnetic field of arbitrary strength, was studied in the mid 1980's by Dokuchaev [Sov. Phys. JEPT 65 (6), 1079 (1986)] [29], by using the Ernst-Wild metric, which is an exact solution of the Einstein-Maxwell equations. This is a stationary, axisymmetric magnetic universe having a magnetic field of arbitrary strength enshrouding a rotating, electrically charged BH. As such, this metric generalizes the Kerr-Newman solution to the case in which there is a magnetic field of strength B_0 parallel to the BH rotation axis, by changing the Kerr-Newman functions f_0 and ω_0 to new functions f and ω defined as: $f = f_0|\Lambda|^{-2} f_0$; with $\Lambda = 1 + B_0\Phi_0 - \frac{1}{4}B_0^2\Xi_0$, and $\omega = (\alpha - \beta\Delta)(r^2 + a^2)^{-1}$ (The reader is addressed to Section 2. of Ref. [29] for the definition of the potentials Φ_0 and Ξ_0, and other variables here referred to, and for a thorough discussion of the BH-B_0 interaction in the extreme regime). The analisys of the more general case, which allows for the effect of the magnetic field to act back on the BH, leads to one key result of this work: the finding that the BH may have angular momentum and electric charge that exceeds those allowed for Kerr-Newman BH. This enhancement may substantially alter the energetics of the BH-torus system, and of course the total GWs energy released in the process.

[‡] Relevant to Eq.(23) is to note that Kluźniak and Ruderman [35] and Ruderman, Tao and Kluźniak [36] have shown that transient differential rotation at the interior of a millisecond spinning proto-neutron star (supposed to be the GRBs central engine) may drive polar fields of strength: $B = [f\rho c_s^2(8\pi)]^{1/2} \sim 10^{17}$G, if a fractional composition between interior and subsurface layers: $f \sim 0.02$ is assumed (see details and definitions in Ref. [35]). These fields are shown to exist for: $\Delta T_{B_{\phi(equip)}} \sim 10^{-2}$s. Also interesting is the fact that the equipartition poloidal field of a NS of gravitational binding energy $\simeq 10^{-1}{\rm M_{NS}}c^2$ is $B_{\phi(equip)} = B_0 \simeq 10^{18}$G. We conjecture that a field such as this could be inherited during the transient in which the proto-neutron star collapses to form the BH-torus system, in the Van Putten's or Ruffini et al.'s mechanism.

efficiency estimated above leads to a total GWs energy converted into EMWs: $E_{\rm GWs-EMWs} \sim 5 \times 10^{49}$erg, which is nearly of the order of magnitude of the total luminosity in radio received from SN1998bw [1]. Thus the GWs-EMWs conversion mechanism may certainly provide a satisfactory explanation of such an anomalous radio luminosity.

C. Induced E-M Field Strength

To estimate the amplitude ($\bar{E}$) of induced E-M field we set (for $c = G = 1$): $b \equiv \bar{E} = -\bar{B}$, and $a(z) = \kappa \bar{h}^{TT}_{\nu(R_{int})}$, where $\bar{h}^{TT}_{\nu(R_{int})} \sim 10^{-3}$ is $\bar{h}^{TT}_{\nu}$ calculated at the interaction radius[§], with $\bar{h}^{TT}_{\nu}$ given as h_{eff} in Eq.(14) [7]. The efficiency Eq.(23) can be rewritten as the ratio between the EMWs and GWs amplitudes [7] at the radiation zone as

$$\sqrt{\eta'} \equiv \left| \frac{\bar{E}}{\bar{h}^{TT}_{\nu(R_{int})}} \right| = \frac{-i\kappa}{2} \int B(z) dz. \qquad (25)$$

To get some numbers, one may assume the magnetic field decays as a dipole one: $B(z) = B_0 \left(\frac{R_{\rm BH}}{r}\right)^3$, with $R_{\rm BH} < r < R_{\infty}$, $\kappa = \omega/c$, and $\omega/2\pi = f_{GW} = 2$kHz, then the amplitude of the induced electric field, for $R_{int} << r$, turns out to be [7]

$$E_{y\max} = -B_{x\max} \sim 5 \times 10^{13} \frac{\rm V}{\rm m} = 50 \frac{\rm TV}{\rm m}. \qquad (26)$$

Such a large value of the electromagnetic field strength outcomes from the very high magnetic field around the source, which is several orders of magnitude larger than the one for canonical neutron stars: $B \sim 10^{12}$G. Furthermore, to recover the standard fireball model one should recall that very far from the source the MHD evolution of the fireball described above, allows the electron quiver velocity to achieve relativistic values:

$$V(r) \sim \left[\frac{q}{m\omega}\right] \left(\frac{R^3_{int}}{r_{rel}}\right) E_{y\max} \sim c \qquad (27)$$

at a distance from the BH

$$r_{rel} \sim 10^{[15-17]}{\rm cm}, \qquad (28)$$

which depends on the external magnetic field strength. Such a distance scale nearly matches the fireball scale radius, usually referred to as the *deceleration radius* [14]:

$$R_{dec} = \left(\frac{E(LF)}{\frac{4}{3}\pi n_1 L F^2}\right)^{1/3} \sim 10^{16} cm, \qquad (29)$$

which is a typical value inferred from observed radio afterglows [1].

V. PHOTON FREQUENCY MAGNIFICATION AND ANOMALOUS LIGHT CURVES IN GRBS-SNE

A. Photon acceleration in strongly magnetized plasmas

Before discussing the possible explanation of the several anomalies observed in the light curves of a number of GRBs, in particular GRB980326 [11], and more crucially GRB980425 and its associated supernova SN1988bw [1,2], first we shall review, following Ref. [10] from which more details can be obtained, the basics of the physics supporting the idea of frequency magnification due to high density contrasts in the surrounding plasma driven by GWs:

a) we assume a spacetime perturbation (the metric) of GWs propagating along the z-axis given as

$$ds^2 = -dt^2 + [1 + h(u)]dx^2 + [1 - h(u)]dy^2 + dz^2, \qquad (30)$$

with $h << 1$ and $u = z - ct$.

b) the Maxwell's equations in the oscillating metric read:

$$F^{\mu\nu}{}_{;\nu} = \mu_0 J^{\mu} \qquad (31)$$

and

$$F_{\mu\nu;\rho} + F_{\rho\mu;\nu} + F_{\nu\rho;\mu} = 0, \qquad (32)$$

where the gravity induced electric (E) and magnetic (B) current densities are defined as

$$j^1_E = j^2_B = \frac{1}{2}[E^1 - B^2]\frac{\partial h}{\partial z}, \qquad (a)$$

$$j^2_E = -j^1_B = \frac{1}{2}[E^2 + B^1]\frac{\partial h}{\partial z}, \qquad (b)$$

c) the hydrodynamics (HD) of the perturbed plasma (up to first order in h) can be described by

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\vec{v}) = 0, \qquad ({\rm HDa})$$

$$\left[\frac{\partial}{\partial t} + \vec{v} \cdot \nabla\right] \gamma_e \vec{v} = \frac{q}{m}[\vec{E} + \vec{v} \times \vec{B}], \qquad ({\rm HDb}),$$

where the electric field $\vec{E} = E_2 e_2$ is the external magnetic field $\vec{B} = B_0 e_1$ the local electron Lorentz factor (not the fireball Lorentz factor (LF) referred to above) (see details in Ref. [10]),

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[§] Note that in Ref. [6] the term $\bar{h}$, the GWs effective amplitude, is defined in a different fashion, i.e.,

$$\bar{h} \equiv (R_{\rm NS} \times R_{int})^{-1} \sim 10^{-3}. \qquad (24)$$

$$\gamma_e \equiv [1-v_z^2]^{-1/2} :: \text{with} \quad e_3 = z, \quad \text{and} \qquad n = n_0 \quad (33)$$

the local plasma number density. From the Faraday's law one obtains: $\Delta B = E_2 + hB_0$, where ΔB is the perturbation of the external field B_0. Since the currents are determined by the equation of motion, then we one gets:

$$v_z = -\frac{E_2}{B_0 + \Delta B}, \tag{34}$$

while the continuity equation renders the perturbed part of the density

$$\Delta n = n_0 \left[\frac{v_z}{1-v_z}\right] = \frac{n_0}{2}\left(\frac{1}{[1-H_P]^2} - 1\right), \tag{35}$$

with $h \equiv \bar{h}^{TT}_{\nu(R_{int})}$ the parameter H_P can be written as

$$H_P \equiv \frac{2\bar{h}^{TT}_{\nu(R_{int})}}{\sum_i (\omega^2_{P(i)}/\omega^2_{c(i)})}. \tag{36}$$

The GWs amplitude at the interaction zone, $\bar{h}^{TT}_{\nu(R_{int})}$, was computed earlier when considering the lumpiness of the torus encircling a rapidly rotating BH, the remnant of a supernova explosion which triggers a given γ-rays event, as for instance SN1998bw and GRB980425 [1]. The oscillation frequency of each species (i) in the unperturbed plasma reads:

$$\omega_{P(i)} \equiv \left(\frac{q^2_{(i)} n_0}{\epsilon_0 m_{(i)}}\right)^{1/2} \sim 10^{11}\text{Hz} \tag{37}$$

for an electron number density: $n_0 \sim 10^{12}$ cm^{-3}, and $\omega_{c(i)} \equiv \frac{q_{(i)}}{m_{(i)}} B_0$ the cyclotron frequency of the respective plasma species. From this equation it is apparent that any GWs perturbation may drive significant density perturbations whenever the plasma is strongly magnetized, i.e. $\sum_i \omega^2_{p(i)}/\omega^2_{c(i)} << 1$. Meanwhile, for $|\Delta B| >> |hB_0|$, which is the study case here, the set of equations above lead to the crucial and simple relation [10]

$$\frac{\Delta n}{n_0} = \frac{\Delta B}{B_0}, \tag{38}$$

between the perturbed and unperturbed variables characterising the plasma interacting with the GWs near their source. Since these density perturbations are driven by GWs they propagate at the velocity of light, too, that is they are Einstein's GWs. Because the growth is linear in both z and/or t, $H_P \geq 1$, then the GWs induced currents cannot stop the growth of the EMWs, which can thus achieve extremely large amplitudes (as shown in Section IV-C), as far as long coherent interaction length scales are allowed. Notice further that Thompson scattering in the interstellar plasma may preclude to go far too long. More precisely, there exists a maximum length scale constrained by the magnetic field perturbation: $\Delta B_{max} \simeq \Lambda_{crit} \times B_0 \times \frac{\partial h}{\partial(z-t)}$.

To estimate the effect of GWs on high energy photons, i.e., photons with frequency $\omega >> \omega_{P(i)}, \omega_{c(i)}$, let us describe them by the vector potential: $\vec{A} = A_0 e^{\pm i\theta}$, and wave equation: $[\Box + \omega_P^2]\vec{A} = 0$, so that their frequencies satisfy the dispersion relation: $\omega^2 = \kappa^2 c^2 + \omega_P^2(z-t)$. Thence the magnification of the photon frequency is straithforwardly derived from the classical *ray equations*

$$d\kappa/dt = -\partial W(z-t)/\partial z \tag{39}$$

and

$$d\omega/dt = \partial W(z-t)/\partial t. \tag{40}$$

Considerations about the waves' group velocity and the properties of the W function leads to a magnification relation:

$$\mathcal{M} \equiv \frac{\omega_2}{\omega_1} = \frac{\omega^2_{P_2}}{\omega^2_{P_1}} \tag{41}$$

where the subscripts 1, 2 refer to the time at which the photon gets to (leaves) the region with a minimum (maximum) given density gradient, respectively. Since the magnification factor does not depend upon the frequency bandwidth of the EMWs, it is clear that in principle one can convert x-rays into γ-rays, in the same fashion as for radio turned into visible light, for instance. Thus, photons propagating in a moving density gradient driven by GWs may be up-converted (or down-converted), depending on the ratio written down in Eq.(41), whose effect can be quite large.

Let us now turn back to our study case. Firstly, notice that the BH in GRB980425/SN1998bw was suggested to be rotating with period $\sim 10^{-4}$ s. This spin rate is inferred from the conservative relation: $\Omega_{torus}/\Omega_{BH} \simeq 10^{-1}$, as demonstrated by van Putten [8,27]. Consequently, because of the analogy with pulsar magnetospheres quoted above as used by van Putten [8,27], we can estimate the transient variation of the local magnetic field in the plasma region where the conversion takes place as:

$$\frac{\Delta B}{B_0} \sim 10^5, \tag{42}$$

or equivalently

$$\mathcal{M} = \frac{\omega_{max}}{\omega_{min}} \sim 10^5, \tag{43}$$

for the GWs amplitude estimated above. Thus, the 2kHz EMWs from the GWs-EMWs conversion and the 10kHz EMWs from the BH spindown can be shifted to GHz frequencies by this photon acceleration process. Equivalently, infra-red EMWs ($\sim 10^{13}$Hz) can in principle be shifted to the (BeppoSAX) x-ray band ($\sim 10^{17-18}$Hz) of the E-M spectrum directly, i.e., with no need of the fireball Lorentz factor. If this radiation were carried away by the fireball, then they would be turned into hard γ-rays, driven by the fireball characteristic Lorentz factor $\sim 10^3$ [13], producing a notorius enhancement in the γ-ray luminosity of such event. We stress, however, that this is not the case under discussion here.

Overall, there exists still an even more intriguing possibility, γ-rays could be *down-converted* into visible light if the density contrast were at some instant: $\frac{\Delta n}{n_0} \sim 10^{-5}$, which could take place in the intermediate radiation zone (region II in [10]). This density contrast straithforwardly fix the GWs strain during the conversion via H_P defined above. If such a process actually occurred during GRB980425, it might explain the fact that SN1998bw was unsually optically luminous for being a Type Ib/c supernova [22], at its inferred distance $\sim$ 38 Mpc [1]. In the same lines, the proposed down-conversion mechanism could account also for the SN1998bw relatively low flux in x-rays: $f_X < 10^{-13}$ erg cm^{-2} s^{-1}, as observed by BeppoSAX during the first week of the outburst. In a work in preparation we tackle these possibilities in more quantitative fashion [25].

B. Second radio peak in SN1998bw light curve: GWs trapped by plasma?

Concerning to the second anomaly in the SN1998bw light curve, a consistent explanation for the appearance of the second peak in the (radio)light curve of SN1998bw can proceed as follows (details of its physics will be given elsewhere [24]): after the shock of the fireball blast wave front with the interstellar medium (ISM), the injection of energy from the GWs-EMWs conversion into the ahead shocked medium, makes it the resulting plasma a turbulent flux driving a local amplification of the magnetic field in the region and an increase of density, too. Such high density gradients (moving at c) could induce excitation of MHD waves in that dense plasma leading potentially to absorption of the GWs. The resulting hydrodynamics may change the plasma frequency to the level at which its frequency matches the one of the outcoming EMWs, forcing the EMWs to get trapped in the shocked plasma. In other words, absorption by the surrounding rarified turbulent plasma, of the EMWs from the GWs conversion, can take place in the supernova debris, as suggested in Ref. [37]. Put it this way, if there were no conversion at all in the event the trend of the SN1998bw radio afterglow would have been the one delineated by the exponential decay of the first peak in its light curve. A feature clearly visible in Figure 1 in Ref. [1]. However, if the conversion actually develops, as argued in this paper, then, in the comoving reference frame, the EMWs from the plasma debris are left behind the fireball-ISM interface (the proper GRB afterglow). Then, special relativistic effects associated with the fireball expansion respect to the observer and respect to the plasma debris will cause the arrival time-delay of these radio waves from the conversion respect to the "proper" radio afterglow. By using the relative space-time transformations of Ruffini et al. [38] it is easy to see that this time-delay corresponds aproximately to 25-35 days after the arrival of the early radio afterglow, the proper radio afterglow. This elapsed time lag agrees with the timescale appearing in Figure 1 of Ref. [1].

Thence, once the radio waves from the GWs conversion start to sum up to the already fading proper radio afterglow this might cause the appearance of a kind of deep valley in the SN1998bw radio-light curve, due to the superposition of both different signals. Over some weeks, once the shocked material in the proper afterglow has relaxed to the ISM dominant conditions and its radio emission has gone, the overall (piled up) radio waves from the plasma debris around the BH may definitely dominate the total radio emission from SN1998bw leading to a rebrightning of the source which may resemble the hump observed about 30-40 days after the SN1998bw radio afterglow risetime [1]. This phenomenology is a sort of reminiscence of the one already observed in GRB980326 by Bloom et al. [11] and also in GRB990712 by Björnsson et al. [12], as discussed in Section I. The same phenomenology manifesting itself in such a wide electromagnetic spectrum is quite suggestive of a subjacent similar physics in those distint GRB events. Thus the GRBs/SNe may be supported by the present mechanism, too.

VI. CONCLUSIONS

As a summary, the theory introduced above might be extended to cover afterglows in other GRBs wavelengths, and also the SNe/GRBs association itself. This can include optical afterglows for which there exists evidence for an important enhancement, or optical depletion as well [11]. It is stressed then that the conversion of GWs-EMWs may actually play a fundamental role in the calorimetry of GRBs and also in the dynamics of a SN explosion as a whole. In that sense, the mechanism claimed in this paper may support the suggestion that some supernovae could be the actual sources of a kind of GRBs [1]. A careful analysis, based on this mechanism, of the energetics of GRBs/SNe associations to be observed in the future may help to settle down the actual controversy.

The sort of GWs sources needed to make it viable the GWs-EMWs conversion here discussed, involve essentially the kind advocated by van Putten [8] from magnetized black holes-torus systems in which the GWs energy stem from the rotational energy of the BH and/or torus, mainly. One can expect, nonetheless, that the physics of GWs-EMWs conversions as presented above behaves almost equivalently in the context of the "dyadosphere" mechanism for the central engine of GRBs promoted by Ruffini et al. [26], where for a $10 M_\odot$ BH also about 3×10^{53} erg may be released as GWs at the EMBH formation. This is a work in preparation [24]. Other GWs sources able to satisfy the conversion constraints and provide the energetics and timescale required for the mechanism to suitably work can also be exploited.

Overall, the proposed conversion mechanism may turn GRBs-SNE associations potential targets for the planned Low Frequency Radio Antenna (LOFAR) and the Square Kilometer Array (SKA) radio-observatories, which can operate in coincidence with the GWs interferometric observatories LIGO, VIRGO, GEO-600, TAMA, etc. This is a estimulating perspective for the near future. Therefore, if the conversion in this paper promoted proves to be accomplished in these GRBs-SNe events, then opposite to the claim by Marklund, Brodin and Dunsby [6] that no available radiotelescope is able to detect these radiowaves, I suggest that the observed luminosity enhancement in radio from SN1998bw would constitute the most novel astrophysical evidence for the existence of GWs. There are two major reasons for these opposing conclusions: a) although Marklund et al. [6] did work out an astrophysical scenario in which the conversion process may occur, it is unclear if this coalescence of a binary neutron star is able to give up a remnant endowed with an extremely high magnetic field so as to largely increase the GWs-EMWs efficiency on the base of Eq.(23)**. b) a more crucial difference concerns with the total gravitational radiation emitted by the source. While the coalescence process is estimated to produce at most about $[10^{-4} - 10^{-6}] M_\odot c^2$ in GWs [39,40], the mechanism here invoked, based on Van Putten's [8] (and Ruffini et al.'s [9]) mechanism for driving GRBs, releases an energy of about 1 $M_\odot c^2$ in gravity waves! In addition, they did not consider in Ref. [6] the possibility of a several orders of magnitude frequency enhancement of the very long wavelength radio ([1-2] kHz) generated by the late inspiraling and merger. The idea concerning the large frequency amplification was developed shortly later in a work by Brodin et al. [10], in which they emphasize the tight constraints for it to actually occur and the validity of the physical assumptions done in deriving the new results. As such, GRBs-SNe associations could be pointing towards a new window to look for GWs in high energy astrophysical events.

ACKNOWLEDGMENTS

I would like to thank the anonymous referee for his (her) criticisms and crucial suggestions which led to the highly improved present manuscript. I also thank Prof. R. Ruffini and the International Centre for Relativistic Astrophysics (ICRA) - International Coordinating Centre, Pescara (Italy), for hospitality and support during part of the preparation of this work. HJMC is a fellow of the Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ), under the grant E-26/150.705/2001.

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** This is so since most (canonical) neutron stars are known to be born possessing a mass $\sim 1.4 M_\odot$ and a typical magnetic field $\sim 10^{12}$G, while is unclear whether or not the turbulent coalescence may amplify the pre-existent fields through alpha-dynamo effect, as quoted earlier.

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