Gravitational-to-electromagnetic wave conversion and gamma-ray bursts calorimetry: The GRB980425/SN 1998bw $\sim 10^{49}$ erg radio emission

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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.* At its peak SN 1998bw was anomalously superluminous in radio wavelengths with an inferred fluence $E_{\rm radio} \geqslant 10^{49}$ erg [S. Kulkarni *et al.*, Nature (London) **395**, 663 (1998)], while the apparent expansion velocity of its ejecta ($\sim 10^{-5} M_{\odot}$) suggests a shock wave moving relativistically ($V_{\rm exp} \sim 2c$). The unique properties of SN 1998bw strengthen the case for it being linked with GRB980425. I present a consistent, novel mechanism to explain the peculiar event SN 1998bw and similar phenomena in GRBs: Conversion of powerful, high frequency ($\sim$2 kHz) gravitational waves (GWs) into electromagnetic waves [M. Johnston, R. Ruffini, and F. Zerilli, Phys. Rev. Lett. **31**, 1317 (1973)] might have taken place during SN 1998bw. Yet, conversion of GRB photons into GWs, as advanced by 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 plausibly induce *dark* GRBs, those with no optical afterglow. The class of GWs needed to drive the calorimetric changes of these gamma-ray bursts may be generated by (a) the nonaxisymmetric dynamics of a torus surrounding the hypernova (or failed supernova) magnetized stellar-mass black hole (BH) remnant, as in van Putten's mechanism for driving long GRBs powered by the BH spin energy [Phys. Rev. Lett. **87**, 091101 (2001)], or in the van Putten and Ostriker mechanism to account for the bimodal distribution in duration in GRBs [Astrophys. J. Lett. **552**, L32 (2001)], where the torus magnetohydrodynamics may be dominated by either hyperaccretion onto a slowly spinning BH or suspended accretion onto a fast rotating BH, or (b) the just formed black hole with electromagnetic structure as in the GRB central engine mechanism of Ruffini *et al.* [Astrophys. J. Lett. **555**, L107 (2001); **555**, L113 (2001)], provided the issue concerning the origin of the black hole charge can be suitably clarified. In both of these mechanisms the total energy radiated as GWs is about $\Delta E_{\rm GW} \sim 10^{53}\,{\rm erg} \times (M/10 M_{\odot})$, which for the conversion efficiency estimated here turns out to be enough to explain the superluminous radio wavelength emission from SN 1998bw. Thus, I argue this process could have induced the enhancement in the radio luminosity of SN 1998bw as evidenced in its light curve [Fig. 2, in S. Kulkarni *et al.*, Nature (London) **395**, 663 (1998)] and optical light curves of GRB980326 [J. Bloom *et al.*, Nature (London) **401**, 453 (1998)] and GRB990712 [G. Björnsson *et al.*, Astrophys. J. Lett. **552**, L121 (2001)]. Moreover, GW-driven plasma density perturbations moving at the speed of light may up- (or down-) convert fireball photons, which could cause further substantial modifications of the gamma-ray burst or supernova calorimetry.

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I. ASTROPHYSICAL MOTIVATION

Cosmological gamma-ray bursts (GRBs) release energy approaching the rest mass of a neutron star on a time scale 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 inescapable that a bright supernova (SN) should occur along with the GRB, which is expected to leave a black hole (BH) as its remnant. It is arguable that the SN emission (SNE) may compete with the much brighter afterglow generated by the relativistic blast wave triggering the GRB itself. Therefore, the strongest evidence for the massive star origin of the GRB would be to observe a SN coincident with a GRB. Several claims in this direction have been put forward: GRB980326 [1], GRB980425 (SN 1998bw) [2], GRB990712 [3], GRB970228 [4,5], GRB990712 [6,7], GRB980703 [8,9], GRB990510 [9], and GRB970508 [10]. Below we exploit 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 GRB leading scenario, the fireball model [11—13] has successfully explained what is going on in the cosmological sources of GRBs and in their afterglows (Refs. [12,14–17], and references therein). A fireball, a huge concentration of radiation plus an opaque electron-positron plasma, released in a small space, is the analogue of a supernova, in which its ejecta, a relativistic blast wave of Lorentz factor $F_L \sim 10^4$, is supposed to trigger the γ surge. It carries so much energy that powering bursts observable from the Hubble distance is not too difficult a task.

A. Anomalous gamma-ray bursts light curves

In the star field around GRB980425, Galama *et al.* [18] discovered an unknown bright optical object lying at the western spiral arm of the galaxy ESO 184-G82, and suggested that the source could be a GRB980425 parental supernova. Spectroscopic observations and their interpretation [19] confirmed SN 1998bw to be a type-Ib/c peculiar supernova located at $z=0.0083$, i.e., 38 MPc. The SN 1998bw radio curve exhibits a rapid early rise within ± 2 days after the time of GRB980425, which further reinforces the possible association. Its peak spectral radio luminosity

$$L_{\rm SN}^{\rm Radio} \sim 4\pi S_6 d^2 \sim 8\times 10^{28}\,{\rm erg\,s^{-1}\,Hz^{-1}} \qquad (1)$$

for $d\sim 38\,{\rm Mpc}$, was larger than for typical type-II supernovae (e.g., SN 1998Z). Its angular radius, which about 10 days after the explosion was $\theta_s \sim 9\ \mu{\rm as}$ [2], was expanding at a velocity of $\geqslant 9\times 10^4\,{\rm km\,s^{-1}}$.

In modeling the radio emission from SN 1998bw Kulkarni *et al.* [2] realized that something was wrong with their estimate of the brightness temperature made using an *incoherent synchrotron model* for the radio emission from SN 1998bw. The resulting temperature $T_{\rm ICC} \leqslant 5\times 10^{11}\,{\rm K}$ was quite low when compared to the inferred brightness:

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

Here S is the flux at wavelength λ (see Ref. [2] 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 works only for explaining the first peak in the light curve; it cannot account for the second one occurring nearly 30 days after the rise [2]. Below I introduce a consistent mechanism to explain these unusual features of SN 1998bw, including a potential explanation for the occurrence of this hump (second peak) in its light curve. Analogous physics might play a role in other GRB-SNE events.

Along the same lines, nearly one month earlier than GRB9890425–SN 1998bw another prospective association between GRBs and SNE was observed: GRB980326 [1]. Optical observations of GRB980326 also showed an unusual light curve [1]. The transient brightened about 3 weeks after the burst, with a flux 60 times larger than the one extrapolated from the rapid decay seen at early time [1]. The GRB980326 spectrum changed very dramatically, turning extraordinarily red quite early. The GRB980326 *R*-band photometry exhibited a characteristic power law decay in the temporal evolution of the flux followed by an apparent flattening. The standard interpretation is 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 [1]. But, surprisingly, Bloom *et al.*'s later observations [1], about nine months after the GRB980326 event, indicated 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.* [1] that the new source is an underlying supernova. Their interpretation then suggested this event as the first evidence for a GRB-SNE connection.

This sort of phenomenological association GRBs/SNE also comes out from the reexamination of the optical afterglow of GRB990712 by Björnsson *et al.* [3]. It was shown that a break in the light curve indeed appears to be present in the *V*-band about 1 or 2 days after the GRB990712 event. Such reanalysis clearly confirmed a prediction based on the study of polarization data, and showed evidences for a collimated outflow with moderate spreading $\theta\sim 6°$. Then, a prominent supernovalike 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 interpretation is that the data provide a tantalizing case for the GRB/SNE association in this event too.

From the above phenomenology one can speculate on the possible conversion of gravitational waves (GWs) into electromagnetic waves (EMWs), and vice versa, 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 discusses theoretical arguments for graviton-photon interconversion. Section III focuses on the most likely mechanisms for the generation of GWs during GRB events. We review sources where the central engine is both a compact (most likely a stellar-mass BH) and a strongly magnetized object, as in van Putten's GWs from a torus orbiting a BH [20]; and Ruffini *et al.*'s mechanism involving a dyadospheric BH, an EMBH [21]. In Sec. IV the efficiency of the GW-EMW conversion process is estimated. The result is used to compute the increase in radio emission from the GRB-SNE association. Section V exploits the possibility of GW-plasma coupling in the conversion region around the BH being involved in raising or dropping the initial frequency of the incident GWs. Some conclusions and potential directions for future research are presented in Sec. VI.

II. RADIO WAVES DUE TO GRAVITATIONAL WAVES

Several authors have considered the possible coupling between GWs and EMWs, including theoretical approaches [20–24] and astrophysical applications [21,25,26]. This process is founded in the equivalence principle on which general relativity is based. Recently, Marklund, Brodin, and Dunsby [24] have demonstrated that conversion of gravitational waves into electromagnetic waves in a background, static homogeneous electromagnetic field may occur. Along the same lines, it was shown by Moortgat [26] that the phenomenon could be relevant for gamma-ray bursts, even without photon acceleration, i.e., frequency enhancement (or decrease) induced by GW-driven density gradients [23]. See also the arguments favoring the GWs-EMWs resonant interaction presented by Mendonça and Drury [49] in which photon acceleration in vacuum can take place.

In this article I suggest that the graviton-photon interconversion mechanism may explain, without any fine-tuning, the energy excess or deplete in the electromagnetic light curve of very energetic phenomena such as SN explosions and/or GRB events, in particular their anomalous[1] (extraluminous or subluminous) light curves. Although EMW emission due to GWs is not a new idea, the very innovative concept I present here concerns the responsibility of GW-EMW conversion for not only the great enhancement in both the SN 1998bw radio [2] and visible light luminosities [30], but also its subluminosity in γ rays and x rays [2]. It also applies to the enhancement in the GRB980326 and GRB990712 optical emission [1]. 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 [31,32], and it would also inaugurate a new perspective in detection of gravitational waves. I stress that the idea presented here is the by-product of the interplay of several pieces of physics and astrophysics currently accepted among researchers in those fields.

A. Constraints on conversion environments

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

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 Fig. 1 in [20]) could transiently achieve supercritical values over a time scale relatively long compared with the period of the GWs emitted, so as to drive long GRBs [20,33]. The region that could satisfy these requirements is the space inside the torus and outside the BH horizon. The characteristic size of this region is about 50 km, a distance scale that is inferred from the stability condition of the torus orbiting the BH. This typical length scale essentially corresponds to the inner GW radiation zone, the region where most of the GW-EMW conversion is expected to take place [24–26]. Note, however, that according to Marklund *et al.* [24] the effective size of the GW-EMW transmitter is determined by either the extension of the (static) magnetic field or the mismatch distance $L \equiv 2k/\pi(\Delta k)^2$, whichever is smaller (here k is the EM wave number). This is due to the fact that the GWs and the extraordinary EMW mode satisfy nearly the same dispersion relation in the regime where $\omega_p^2/\omega_c \ll \omega \lesssim \omega_p \ll \omega_c$ (see the discussion in Sec. V A), which tends to make the linear wave interaction coherent over large distances, i.e., of the order of $L_{\mathrm{coup}} \gtrsim 60 R_{\mathrm{BH}} \sim 1200$ km (see Sec. IV A below). The overall magnetic field in the torus is expected to be inherited from the remnant flux of the GRB progenitor star [20]. In this manner, I suggest, it is possible to obtain a large enhancement in the total EMW luminosity, a high conversion efficiency, which is enough to explain the unusual calorimetry of cosmological GRBs, as evidenced in particular by the radio emission from SN 1998bw [2] and the optical light curves of both GRB980326 [1] and GRB990712 [3].

III. HIGH POWER AND FREQUENCY GRAVITATIONAL WAVES FROM A TORUS ORBITING A BLACK HOLE

Although in this section we shall discuss the mechanism for generating GWs during long GRBs suggested by van Putten [20], the attentive reader should be aware of the fact that essentially the same physics must result if one uses the Preparata *et al.* [34] dyadospheric BH engine mechanism for GRBs, or any other mechanism able to produce GWs with the desired characteristics of energy and time scale, as already highlighted.

Hypernovae and collapsars are the main theories available to account for 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, formed from the supernova fallback material on the timescale

$$\Delta T_{\mathrm{fall}} = \pi \left(\frac{R_{\mathrm{env}}^3}{8 G\, M_{\mathrm{BH}}} \right)^{1/2} > 1 \quad \mathrm{day} \left[\frac{R_{\mathrm{env}}}{10^{12} \mathrm{cm}} \right]^{3/2} \left(\frac{10\ M_\odot}{M_{\mathrm{BH}}} \right)^{1/2}. \tag{2}$$

It has been argued by van Putten [20,35] that a large amount of gravitational radiation from the orbiting torus can be powered by the BH spin energy due to the magnetohydrodynamic (MHD) coupling in the system. Next we follow van Putten's [20,35] main lines of argument to estimate the GW energetics from the stressed torus. In this mechanism the torus is coupled to the spin energy of the BH through its magnetosphere, in an analogous way as in pulsars. The MHD coupling, through Maxwell stresses, drives nonsymmetric instabilities and lumpiness in the torus. The torque

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

applied by the BH, of equilibrium magnetic moment $\mu_{\mathrm{BH}} \simeq a B_\theta J_{\mathrm{BH}}$, 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, and J_{BH} is the BH an-

[1]The term "anomalous" throughout this paper follows the usage of Kulkarni *et al.* [2] of the word "unusual," intended to stand for an event with radio emission several (2–4) orders of magnitude larger than the "usual" (to be read "cataloged") supernovae. A factor of almost 2 characterizes the energetic difference between the two peaks in the radio light curve of SN 1998bw, which thus falls into this category.

gular momentum. $2\pi f_{\rm BH}A$ denotes the flux in interconnecting magnetic field lines, with $f_{\rm BH}\propto(M_{\rm BH}/a)^2$ the fraction of the torus magnetic flux incident on the BH, and $2\pi A=2\pi ab\langle B_\theta\rangle$ the net magnetic flux released from the torus, with a and b the torus principal semiaxes and $\langle B_\theta\rangle$ 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 a long time [20], 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 of the MHD physics in this system the reader is referred to the complete review by van Putten [36].

A. Gravitational waves from suspended accretion around black holes

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 $\Omega_{\rm BH}/\Omega_{\rm torus}\gg 1$. We can estimate the total gravitational and electromagnetic radiation from a torus of ellipticity ϵ, mass $M_{\rm torus}$, and magnetic moment $\mu_{\rm torus}$, spinning around its center of mass, by recalling that its quadrupole magnetic and mass moments read

$$Q^{\rm mass}_{\rm torus}=\epsilon M_{\rm torus}, \quad Q^{\rm EM}_{\rm torus}=\epsilon\mu_{\rm torus}. \tag{4}$$

These relations lead to GW and EMW luminosities of

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

$$L^{\rm EMW}_{\rm torus}=\frac{\epsilon^2}{\pi}[\Omega_{\rm torus}M_{\rm BH}]^4(\mu_{\rm torus}M^2_{\rm BH})^2. \tag{6}$$

It has been shown that only in the presence of magnetic fields unable to provide enough pressure to counterbalance the source gravitational energy density (B fields gravitationally weak, in the usage of Ref. [20]) is the ratio between $L^{\rm GW}_{\rm torus}$ and $L^{\rm EMW}_{\rm torus}$ larger than 1 [20]. However, as is argued in Sec. IV B, this cannot 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 this case, the radio contribution to the calorimetry of GRBs could be dominant so as to appear clearly in the particular light curve of SN 1998bw as a noticeable radio luminosity enhancement.

B. Gravitational wave characteristics

The orbital revolution time scale of the torus can be inferred from its characteristic radius $\langle R_{\rm torus}\rangle\sim M^{7/5}_{\rm BH}\Omega^{2/5}_{\rm BH}\sim 50$ km [20,35] and the orbital velocity of a stably orbiting accretion disk at that distance from a BH of fiducial mass $7M_\odot$, $V_{\rm torus}\sim c/3$. In this way we obtain

$$\Delta T_{\rm orb}\equiv\frac{\langle R_{\rm torus}\rangle}{V_{\rm orb}}\sim 1\times10^{-3}\text{–}5\times10^{-4}\ {\rm s}. \tag{7}$$

Although the GW frequency undergoes a constant chirp, i.e., $df_{\rm GW}/dt=$const, this time scale determines the frequency of the GWs emitted during the orbital evolution of the torus lumpiness as

$$f_{\rm GW}\equiv 2\times(\Delta T_{\rm orb})^{-1}=2\text{–}4\ {\rm kHz}. \tag{8}$$

The GW luminosity $L_{\rm GW}$ as a function of the BH luminosity $L_{\rm BH}$ can be obtained from the equilibrium conditions for the torque and energy in the suspended accretion state (see details in Refs. [20,35]). Since the equivalence in poloidal topology to a pulsar magnetosphere indicates that a large amount of the BH luminosity is incident onto the magnetized material compressing the torus, that is, most of the magnetic field on the horizon is anchored to the surrounding matter, the total luminosity at the BH horizon can be estimated as

$$L_{\rm BH}\simeq L_{\rm torus}=\Omega_{\rm torus}(\Omega_{\rm BH}-\Omega_{\rm torus})f^2_{\rm torus}A^2_{\rm BH}. \tag{9}$$

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

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

Then, the GW luminosity can be recast as

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

Because the spin energy available from a maximally rotating BH is

$$\Delta E_{\rm BH}\simeq 4\times10^{53}\left(\frac{M_{\rm BH}}{7M_\odot}\right)\ {\rm erg}, \tag{12}$$

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

$$\Delta E_{\rm GW}\simeq 10^{53}\left(\frac{M_{\rm BH}}{7M_\odot}\right)\ {\rm erg}. \tag{13}$$

Finally, from Eq. (13) we arrive at the effective GW amplitude

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

This relation produces $h_{\rm eff}\sim10^{-21}$ for a GRB event at a distance of $\sim$100 Mpc. It was shown in Ref. [20], that a GW signal such as this could be detected by the Laser Interferometric Gravitational Wave Observatory (LIGO-I), VIRGO, and GEO-600 interferometers, which in passing turns long GRBs into a prospective target for GW detection.

IV. GRAVITATIONAL-ELECTROMAGNETIC WAVE CONVERSION EFFICIENCY

A. Gravitational-electromagnetic wave 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 equivalence principle holds. This idea was originally discussed by Ruffini in the early 1970s [22], and very recently in Refs. [24,26–29]. Thus it is possible to estimate the efficiency in the EMW-GW conversion process by solving the linearized field equations for the *resonant term* of the z-axis outcoming EM field with wave vector $|\vec{\kappa}|=\kappa_z=\omega/c$, 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 $F^{(0)\mu\alpha}$. This term is the only relevant part of the stress-energy tensor of plane EMWs with amplitudes normalized to the GW total energy density $T^{\rm GW}_{\mu\nu}=(c^4/16\pi G)\langle h^{TT}_{ij,\mu}h^{TT}_{ij,\nu}\rangle$. From the Einstein equations, we thus get the wave equation [26]

$$\Box\phi^{\mu}_{\nu}=\frac{-8G}{c^4}\left(F^{(0)\mu\alpha}F_{\nu\alpha}-\tfrac{1}{4}\,\eta^{\mu}_{\nu}F^{(0)\alpha\beta}F_{\alpha\beta}\right)$$

$$=-\frac{8G}{c^4}F^{(0)\mu\alpha}F_{\nu\alpha}, \tag{15}$$

where

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

As stated just above, the GW energy density reads

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

with the metric being given as

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

where $\varsigma^{\mu\nu}\varsigma_{\mu\nu}=1$ and $\varsigma^{\mu}_{\nu}=0$. The electromagnetic energy density (the Poynting flux) is given by

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

where the EM field is given as

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

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

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

$$\Box\phi^{\mu}_{\nu}=\left(\frac{16G}{c^4\kappa^2}\right)^{1/2}\frac{\varsigma^{\mu}_{\nu}}{\kappa_z}\left(\kappa_\alpha\kappa^\alpha+\frac{d^2a(z)}{dz^2}+2i\kappa_z\frac{da(z)}{dz}\right)e^{i\kappa_\beta x^\beta}$$

$$=-\frac{16\pi\sqrt{\pi}bG}{c^4}F^{(0)\mu\alpha}f_{\nu\alpha}e^{i\kappa_\beta x^\beta}. \tag{21}$$

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

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

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

B. Conversion efficiency and SN 1998bw 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 GW-EMW conversion may be computed from Eq. (22) as [26]

$$\eta\equiv\left|\frac{a(z)}{b}\right|^2=\frac{4G}{c^4}F^{(0)2}L^2_{\rm coup}=5\times10^{-4}\left[\frac{B_0}{10^{18}\,{\rm G}}\right]^2\left[\frac{L_{\rm coup}}{10^3\,{\rm km}}\right]^2, \tag{23}$$

with $L_{\rm coup}$ 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 GW-EMW interaction is $L_{\rm coup}\sim10^3$ km, namely, the region III in Refs. [26,24]. This distance scale for conversion to occur is defined as the interaction radius $R_{\rm int}$, which is roughly equivalent to about 3–4 times the GW wavelength $\lambda_{\rm GW}\equiv c\times\Delta T_{\rm orb}\sim300$ km. We have also considered that the magnetic field (if of dipole nature) in the BH surroundings ($\sim10^2$–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 GW-EMW conversion 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 magnetohydrodynamic turbulence and mixing (as pointed out by van Putten [20]) may also occur. Such effects are also well known to drive entanglement of preexisting (the SN core remnant) magnetic fields, which may potentially be amplified to the values quoted here during the transient time over which the GRBs and GWs are emitted and the radio conversion process develops.

At this point a word of caution must be put forward: The van Putten mechanism for GRBs is based on the existence 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. A BH-torus system pervaded by a superstrong magnetic field is an ''ill-understood'' limit that still deserves a more detailed analysis. Nonetheless, we stress that this 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 to the point where it raises questions about our results.[2]

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 ultrahigh energy particles (protons, for instance) are observed to occur. It is highly plausible that an analogous phenomenology develops in stellar-mass BH tori, as in miniquasars. Finally, recent studies suggest that $B_{\rm core}^{\rm SN} \sim 10^{20}-10^{21}$ G [38–42] can exist in the interiors of newly created neutron stars (NSs) having ferromagnetic or deconfined quark cores ($R_{\rm core} \sim 5$ km), where neutron motion is quantized. Assuming that the formation of a NS corelike structure precedes the BH formation, it follows that the conjectured B field in Eq. (23) is not so unlikely to exist transiently around the remnant torus. Then $B \sim 10^{18}-10^{17}$ G can certainly permeate the interaction region on this basis.[3] Finally, a closing remark concerning the conversion efficiency itself: There exists a theoretical prediction by Johnston, Ruffini, and Zerilli [25] that the conversion efficiency could be as high as some percentage of the total GW energy produced in the process, instead of 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 GRB overall calorimetry through the process invoked in this paper. This more intriguing issue deserves more careful reconsideration.

Consequently, by using Eq. (13) the efficiency estimated above leads to a total GW energy converted into EMWs of $E_{\rm GW\text{-}EMW} \sim 5\times 10^{49}$ erg, which is nearly of the order of magnitude of the total radio luminosity received from SN 1998bw [2]. Thus the GW-EMW conversion mechanism may certainly provide a satisfactory explanation of such an anomalous radio luminosity.

C. Induced electromagnetic field strength

To estimate the amplitude $(\overline{E})$ of the induced EM field we set (for $c=G=1$) $b \equiv \overline{E} = -\overline{B}$ and $a(z) = \kappa \overline{h}^{TT}_{\nu(R_{\rm int})}$, where $\overline{h}^{TT}_{\nu(R_{\rm int})} \sim 10^{-3}$ is $\overline{h}^{TT}_{\nu}$ calculated at the interaction radius,[4] with $\overline{h}^{TT}_{\nu}$ given as $h_{\rm eff}$ in Eq. (14) [26]. The efficiency Eq. (23) can be rewritten as the ratio between the EMW and GW amplitudes [26] in the radiation zone as

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

To get some numbers, one may assume the magnetic field decays as a dipole one: $B(z) = B_0(R_{\rm BH}/r)^3$, with $R_{\rm BH} < r < R_\infty$, $\kappa = \omega/c$, and $\omega/2\pi = f_{\rm GW} = 2$ kHz. Then the amplitude of the induced electric field for $R_{\rm int} \leqslant r$ turns out to be [26]

$$E_{y\,\rm max} = -B_{x\,\rm max} \sim 5\times 10^{13}\ \text{V/m} = 50\ \text{TV/m}. \tag{26}$$

Such a large value of the electromagnetic field strength is the result of 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:

$$V(r) \sim \left[\frac{q}{m\omega}\right]\left(\frac{R_{\rm int}^2}{r_{\rm rel}}\right) E_{y\,\rm max} \sim c \tag{27}$$

at a distance from the BH of

$$r_{\rm rel} \sim 10^{15}-10^{17}\ \text{cm}, \tag{28}$$

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[2]It is relevant here to remark 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-1980s by Dokuchaev [37], 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 referred to Sec. II of Ref. [37] for the definition of the potentials Φ_0 and Ξ_0, and other variables referred to here, and for a thorough discussion of the BH-B_0 interaction in the extreme regime). The analysis of the more general case, which allows for the effect of the magnetic field reacting 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 exceed those allowed for a Kerr-Newman BH. This enhancement may substantially alter the energetics of the BH-torus system, and of course the total GW energy released in the process.

[3]Relevant to Eq. (23), note that Kluźniak and Ruderman [43] and Ruderman, Tao, and Kluźniak [44] have shown that transient differential rotation in the interior of a millisecond spinning protoneutron star (supposed to be the GRB 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 of $f \sim 0.02$ is assumed (see details and definitions in Ref. [43]). These fields are shown to exist for $\Delta T_{B_{\phi(\rm equip)}} \sim 10^{-2}$ s. Also interesting is the fact that the equipartition poloidal field of a NS of gravitational binding energy $\simeq 10^{-1} M_{\rm NS}c^2$ is $B_{\phi(\rm equip)} = B_0 \simeq 10^{18}$ G. We conjecture that a field such as this could be inherited during the transient in which the protoneutron star collapses to form the BH-torus system, in van Putten's or Ruffini *et al.*'s mechanism.

[4]Note that in Ref. [24] the term $\overline{h}$, the GW effective amplitude, is defined in a different fashion, i.e.,

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

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* [12]:

$$R_{\rm dec}=\left(\frac{E(F_L)}{\frac{4}{3}\pi n_1 F_L^2}\right)^{1/3}\sim 10^{16}\,{\rm cm}, \tag{29}$$

which is a typical value inferred from observed radio afterglows [2].

V. PHOTON FREQUENCY MAGNIFICATION AND ANOMALOUS LIGHT CURVES IN GAMMA-RAY BURST–SUPERNOVA EMISSION

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 [1], and more crucially GRB980425 and its associated supernova SN 1988bw [2,18], we shall first review, following Ref. [13] 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. Note that a rather different physics, leading to nearly similar results, is found in the recent paper by Mendonça and Drury [49].

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

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

with $h\ll 1$ and $u=z-ct$.

(b) The Maxwell's equations in the oscillating metric read

$$F^{\mu\nu}{}_{;\nu}=\mu_0 J^\mu \tag{31}$$

and

$$F_{\mu\nu;\rho}+F_{\rho\mu;\nu}+F_{\nu\rho;\mu}=0, \tag{32}$$

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

$$j_E^1=j_B^2=\tfrac{1}{2}[E^1-B^2]\frac{\partial h}{\partial z},$$

$$j_E^2=-j_B^1=\frac{1}{2}[E^2+B^1]\frac{\partial h}{\partial z}.$$

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

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

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

where the electric field is $\vec{E}=E_2 e_2$, the external magnetic field $\vec{B}=B_0 e_1$, the local electron Lorentz factor [not the fireball Lorentz factor (F_L) referred to above] (see details in Ref. [23]), defined as

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

the local plasma number density. From 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 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 $h\equiv\overline{h}^{TT}_{\nu(R_{\rm int})}$ the parameter H_P can be written as

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

The GW amplitude in the interaction zone, $\overline{h}^{TT}_{\nu(R_{\rm int})}$, 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-ray event, as for instance SN 1998bw and GRB980425 [2]. The oscillation frequency of each species (i) in the unperturbed plasma is given by

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

for an electron number density $n_0\sim 10^{12}\,{\rm cm}^{-3}$, and $\omega_{c(i)}\equiv(q_{(i)}/m_{(i)})B_0$ the cyclotron frequency of the respective plasma species. From Eq. (36) it is apparent that any GW perturbation may drive significant density perturbations whenever the plasma is strongly magnetized, i.e., $\Sigma_i\omega^2_{p(i)}/\omega^2_{c(i)}\ll 1$. Meanwhile, for $|\Delta B|\gg|hB_0|$, which is the study case here, the set of equations above lead to the crucial and simple relation [23]

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

between the perturbed and unperturbed variables characterizing 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, $H_P\gg 1$, then the GW-induced currents cannot stop the growth of the EMWs, which can thus achieve extremely large amplitudes (as shown in Sec. IV C), provided long coherent interaction length scales are allowed. Notice further that Thompson scattering in the interstellar plasma may preclude very long length scales. More precisely, there exists a maximum length scale $\Lambda_{\rm crit}$ constrained by the magnetic field perturbation: $\Delta B_{\rm max} \simeq \Lambda_{\rm crit} \times B_0 \times \partial h/\partial(z-t)$.

To estimate the effect of GWs on high energy photons, i.e., photons with frequency $\omega \gg \omega_{P(i)}, \omega_{c(i)}$, x-rays, to say, let us describe them by the vector potential $\vec{A} = A_0 e^{\pm i\theta}$, and the 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 straightforwardly 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 wave group velocity and the properties of the W function lead to a magnification relation:

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

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 (achromaticity), it is clear that in principle one can convert x rays into γ rays, in the same fashion as for radio waves 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. First, notice that the BH in GRB980425–SN 1998bw was suggested to be rotating with period $\sim 10^{-4}$ s. This spin rate is inferred from the conservative relation $\Omega_{\rm torus}/\Omega_{\rm BH} \simeq 10^{-1}$, as demonstrated by van Putten [20,35]. Consequently, because of the analogy with pulsar magnetospheres quoted above as used by van Putten [20,35], 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

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

for the GW amplitude estimated above. Thus, the 2 kHz EMWs from the GW-EMW conversion and the 10 kHz EMWs from the BH spin down can be shifted to GHz or higher frequencies by this photon acceleration process. Equivalently, infrared EMWs ($\sim 10^{13}$ Hz) can in principle be shifted to the (BeppoSAX) x-ray band ($\sim 10^{17}$–10^{18} Hz) of the EM 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 $\sim 10^3$ [11], producing the notorious enhancement in the γ-ray luminosity of such events. We stress, however, that this is not the case under discussion here, as we show next.

Overall, there still exists an even more intriguing possibility: γ rays could be *down-converted* into visible light if the density contrast were at some instant $\Delta n/n_0 \sim 10^{-5}$, which could take place in the intermediate radiation zone (region II in [13]). This density contrast straight forwardly fixes the GW strain during the conversion via H_P defined above. If such a process actually occurred during GRB980425, it might explain the fact that SN 1998bw was unusually optically luminous for a type Ib/c supernova [30], at its inferred distance $\sim$38 Mpc [2]. On the same lines, the proposed down-conversion mechanism could account also for the SN 1998bw relatively low flux in x rays, $f_x < 10^{-13}\,{\rm erg\,cm^{-2}\,s^{-1}}$, as observed by BeppoSAX during the first week of the outburst. In a work in preparation we tackle these possibilities in a more quantitative fashion [33].

B. Second radio peak in SN 1998bw light curve: Gravitational waves trapped by plasma?

Concerning the second anomaly in the SN 1998bw light curve, a consistent explanation for the appearance of the second peak, the hump, in the (radio) light curve of SN 1998bw can proceed as follows (details of its physics will be given elsewhere [32]). After the shock of the fireball blast wave front on the interstellar medium (ISM), the injection of energy from the GW-EMW conversion into the already shocked medium makes the resulting plasma a turbulent flux driving a local amplification of the magnetic field in the region and also an increase of density. Such high density gradients (moving at c) could induce excitation of MHD waves in the dense plasma, leading potentially to absorption of the GWs. The resulting hydrodynamics may change the plasma frequency to the level at which it matches that of the outcoming EMWs, forcing the EMWs to become trapped in the shocked plasma. In other words, absorption by the surrounding rarified turbulent plasma of the EMWs from the GW conversion can take place in the supernova debris, as suggested in Ref. [45]. Put it this way, if there were no conversion at all in the event, the trend of the SN 1998bw 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 Fig. 2 in Ref. [2]. 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 with respect to the observer and the plasma debris will cause an arrival time delay of these radio waves from the conversion compared to the "proper" radio afterglow arrival time. By using the relative spacetime transformations of Ruffini *et al.* [46] 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 time scale appearing in Fig. 2 of Ref. [2]. Alternatively, this time delay ($\sim$25–30 days) could naturally result as a consequence of a much longer time scale for the BH-torus system to be formed than the one indicated in Eq. (2). The fall-time is longer if the specific angular momentum is significantly large. This is the case in most stars, and it is concommitantly what one expects if such a system is to be the source of the powerful GWs emission needed for the conversion process here advocated to be as efficient as showed above.

Then, once the radio waves from the GW conversion start to increase to the level of the already fading proper radio afterglow, this might cause the appearance of a kind of deep valley in the SN 1998bw radio light curve, due to the superposition of the two 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 SN 1998bw, leading to a rebrightening of the source, which may resemble the hump observed about 30–40 days after the SN 1998bw radio afterglow rise time [2]. This phenomenology is reminiscent of that already observed in GRB 980326 by Bloom *et al.* [1] and also in GRB990712 by Björnsson *et al.* [3], as discussed in Sec. I. The same phenomenology manifesting itself in such a wide electromagnetic spectrum is quite suggestive of underlying similar physics in those distinct GRB events. Thus the GRB-SNE relationship may indeed be supported by the present mechanism.

VI. CONCLUSIONS

As a summary, the theory introduced above might be extended to cover afterglows in other GRB wavelengths, and also the SNE-GRB association and SNE evolution itself. This includes both optical afterglows for which there exists evidence for an important enhancement and optical depletion as well [1]. It is stressed that the conversion of GWs to 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 [2]. A careful analysis, based on this mechanism, of the energetics of GRB-SNE associations to be observed in the future may help to settle the controversy.

The sort of GW sources needed to make viable the GW-EMW conversion discussed here involve essentially the kind advocated by van Putten [20] from magnetized black hole–torus systems in which the GW energy stems mainly from the rotational energy of the BH and/or torus. One can expect, nonetheless, that the physics of GW-EMW 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.* [34], where for a $10M_\odot$ BH about 3×10^{53} erg may also be released as GWs at the EMBH formation. This is a work in preparation [32]. Other GW sources able to satisfy the conversion constraints and provide the energetics and time scale required for the mechanism to work can also be exploited.

Overall, the proposed conversion mechanism may turn GRB-SNE associations into 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 GW interferometric observatories LIGO, VIRGO, GEO-600, TAMA, etc. This is a stimulating perspective for the near future. Therefore, if the conversion promoted in this paper proves to be accomplished in these GRB-SNE events, then in contrast to the claim by Marklund, Brodin, and Dunsby [24] that no available radio telescope is able to detect these radio waves, I suggest that the observed radio luminosity enhancement from SN 1998bw 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.* [24] 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 greatly increase the GW-EMW efficiency on the base of Eq. (23).[5] (b) A more crucial difference concerns 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 [47,48], the mechanism here invoked, based on van Putten's [20] (and Ruffini *et al.*'s [21]) mechanism for driving GRBs, releases an energy of about $1M_\odot c^2$ in gravity waves. In addition, they did not consider in Ref. [24] the possibility of a several orders of magnitude frequency enhancement of the very long wavelength radio waves (1–2 KHz) generated by the late inspiraling and merger. The idea concerning the large frequency amplification was developed shortly afterward in a work by Brodin *et al.* [23], in which the authors emphasize the tight constraints for it to actually occur and the validity of the physical assumptions made in deriving the new results. Thus, GRB-SNE associations could be pointing toward a new window in which to look for GWs in high energy astrophysical events. In addition, the proposed mechanism could also help in understanding the low luminosity of distant supernovae as inferred from the relationship between luminosity and redshift (L vs. z) in a decelerating universe, with no need for a universe *dark energy* component (a small cosmological constant or a quintessence).

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[5]This is so since most (canonical) neutron stars are known to be created possessing a mass $\sim1.4M_\odot$ and a typical magnetic field $\sim10^{12}$ G, while is unclear whether or not the turbulent coalescence may amplify the preexisting fields through the alpha-dynamo effect, as quoted earlier.

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