Fast Radio Bursts *signal* high-frequency gravitational waves

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Abstract

There is growing evidence for high-frequency gravitational waves (HFGWs) ranging from MHz to GHz. Several HFGW detectors have been operating for over a decade, and two GHz events have been reported recently. However, a confirmed detection might take a decade. This essay argues that unexplained observed astrophysical phenomena, like Fast Radio Bursts (FRBs), might provide indirect evidence for HFGWs. In particular, using the Gertsenshtein-Zel′dovich effect, we show that our model can explain three key features of FRBs: generate peak-flux up to 1000 Jy, naturally explain the pulse width and the coherent nature of FRBs. In short, our model offers a novel perspective on the indirection detection of HFGWs beyond current detection capabilities. Thus, transient events like FRBs are a rich source for multi-messenger astronomy.

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It took a century to directly detect gravitational waves (GWs) in the audio frequency range [1]. However, in 1974, Hulse and Taylor indirectly detected GWs using electromagnetic (EM) waves in the radio frequency through the binary pulsar PSR B1913+16 [2]. The indirect detection used the age-old principle — *energy conservation*. It was discovered that the trajectory of a pulsar around a neutron star (NS) gradually contracts with time. This decay in the orbital period matches the loss of energy and momentum in the gravitational radiation predicted by general relativity and the energy released in the form of GWs.

GWs can be generated in various frequency ranges [3–11]. In general, the characteristic frequency of the GW from a compact object is inversely related to object radius R and directly related to mass M [6]:

$$f_0 = \frac{1}{4\pi}\left(\frac{3M}{R^3}\right)^{1/2} \tag{1}$$

In other words, the smaller the object size, the larger the frequency of the GW [3–11]. This is similar to the EM radiation where the frequency depends on the characteristic size of the system that generates it [12]. However, at the beginning of the 20th century, we could only observe the Universe in a narrow band through EM waves. With the advent of radio waves, we now have a wide band of frequencies spanning twenty-orders of magnitude from radio to gamma rays. In that sense, GW astrophysics is in the same stage as astronomy at the start of the 1900s. Similar to how the different spectral ranges of the EM spectrum allow us to understand the Universe differently and to comprehend various events, GWs with *disparate frequencies* can provide distinct perspectives on the cosmos.

As mentioned above, several physical systems can generate GWs in a broad range of frequencies, $10^{-18} - 10^{10}$ Hz [3–11] and direct measurements from different experiments can probe a variety of sources. Since the GW frequency is related to the mass and radius of the object differently [6], and GW weakly couples to matter, one can probe the strong and weak gravity regions to unprecedented accuracy [3–11]. LIGO-VIRGO-KAGRA operating at frequencies less than a few kHz have detected around 100 GW events from merging black-holes and NSs [13–15]. Similarly, nanoGrav and space missions (like LISA and DECIGO) are designed to detect GWs in nanoHz and mHz frequencies [6, 16]. Primordial black-holes, Exotic compact objects, and the early Universe physics generate high-frequency GWs (HFGWs) in MHz to GHz range [17–24]. Over the last decade, many HFGW detectors have been proposed, some of which are operational. For instance, the Japanese 100 MHz detector with a 0.75 m arm-length interferometer has been operational for a decade [17, 18], Holometer detector has put some limit on GWs at MHz [19, 20]. The Bulk Acoustic GW detector experiment recently reported two MHz events after 153 days of operation [23]. A GHz GW detector is also proposed [21].

These detectors are ideally suited for searching for physics beyond the standard model, like primordial black-holes, exotic compact objects, and the early Universe [10]. However, these detectors are in the early stages, and it may take a decade to make a confirmed HFGW detection. This leads us to the following questions: If certain astrophysical mechanisms generate HFGWs, how can they be detected? If we cannot detect these waves directly, do astrophysical phenomena indicate their existence? The kHz GWs events are very short and carry a lot of energy. For instance, during the final moments of LIGO's first detection lasting 0.2 seconds, more energy (10^{20}Jansky) was radiated than the light from all the stars in the galaxy [1, 6]. Extrapolating these features, we see that to detect HFGW signals, one has to look for highly energetic astrophysical events that last for less than a second.

As the binary-neutron star system was a smoking gun for audio-frequency GWs, are there any transient and highly energetic astrophysical phenomena of unknown origin? In the rest of this essay, we argue that Fast radio bursts (FRBs) — extremely energetic millisecond-burst of radio emission produced by the extra-galactic sources [25–27] — can be the *smoking gun* for the existence of HFGWs.

To date, around 700 FRBs have been reported in various catalogs at around 1400 MHz [27–31]. 99% of these FRBs have the following three characteristic features: (i) observed peak flux (S_ν) in the range 0.1 Jy $< S_\nu <$ 700 Jy, (ii) coherent radiation and (iii) pulse width that is less than a second [28, 30]. Since the time scale of these events is less than a second, and the emission is coherent, the astrophysical mechanisms that explain these events *cannot* be thermal [25].

Due to the nature of electromagnetic interaction, small-scale emission mechanisms usually predominate over large-scale coherent electromagnetic processes (like astrophysical masers and pulsar radio emission). Hence, a mechanism that explains FRBs needs to clarify how to generate a large amount of coherent radiation in a short time [32, 33]. This is where gravity helps! While GWs are also generated by accelerating masses, there is one fundamental difference between GWs and EM waves. All masses have the same gravitational sign and tend to clump together to produce large coherent bulk motions that generate *energetic,* *coherent GWs* [34]. Thus, if a mechanism that converts incoming coherent GWs to EM waves exists, we can explain the extremely energetic, coherent nature of FRBs.

Given that GWs as a source can explain coherence, we ask the following questions: Is there a physical mechanism that converts the incoming coherent GWs to EM waves? If that exists, can the necessary conditions for such a mechanism naturally be found in any astrophysical object/region? GWs get converted into EM waves in the presence of a strong transverse magnetic field via the Gertsenshtein-Zel′dovich (GZ) effect [11, 35, 36]. The GWs passing through a region with high transverse magnetic field $\mathbf{B}$ leads to compression and stretching of the magnetic field proportional to $h\mathbf{B}$ (h is the amplitude of GWs), which acts as a source leading to the generation of EM waves. The resultant EM waves generated will have maximum amplitude at resonance (same frequency as incoming GWs) [11, 35, 36]. In quantum mechanical language, the GZ effect is analogous to the mixing of neutrino flavors — the external field *catalyzes* a resonant mixture of photon and graviton states [37]. The external magnetic field provides the extra angular momentum necessary for the spin-1 (photon) field to mix with the spin-2 (graviton) field.

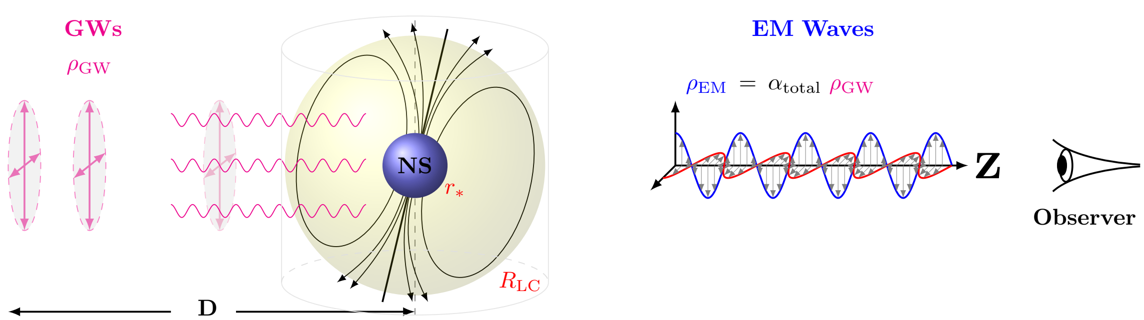

FIG. 1. Schematic depiction of the model to explain FRBs due to HFGWs. The blue sphere is NS with radius r_* and the yellow region around NS corresponds to magnetosphere of radius $R_{\rm LC}$. The black curves correspond to the magnetic field lines. At resonance, the incoming HFGWs (magenta) transmutes to EM waves (blue) in the magnetosphere.

Interestingly, NSs are compact objects with large magnetic fields ($> 10^8$ Gauss), which can lead to a significant conversion of GWs to EM waves. As shown in Fig. 1, consider *transient GWs* produced by exotic compact objects (such as Boson stars, Oscillons, gravastars) passing through the magnetosphere of NS at a distance D (where $D > 10$ kpc). The cylinder around the NS encloses the magnetosphere. GZ effect converts GWs to EM waves as they pass through the magnetosphere [35, 36]. This conversion occurs at all points in the magnetosphere. Consequently, a distant observer (in the z-axis) will perceive this effect occurring in the entire magnetosphere during this brief period. Since the conversion happens at the resonance frequency, as shown below, the FRBs' energy flux depends on the amplitude of the incoming GWs, the magnetic field's strength, and light cylinder radius ($R_{\rm LC}$). [$R_{\rm LC}$ denotes the location where the co-rotation velocity equals the speed of light (see Fig. 1).] Thus, our FRB model has three key ingredients: (i) incoming plane HFGWs, (ii) magnetosphere around the NS, and (ii) conversion from GWs to EM waves. Before we evaluate the energy flux and compare it with observations, we discuss the assumptions about these three key ingredients.

As mentioned earlier, since accelerating masses clump together, they produce large coherent bulk motions that generate *energetic, coherent GWs* [34]. Since we assume NS to be in the radiation zone of the GW emission, the GWs can be treated as plane waves [33]. Thus, the line element of a + (and similarly for ×) polarization mode of GW propagating (with frequency ω_g and wave-vector k_g) along the z-direction, is:

$$ds^2 = d(ct)^2 - (1 + h_+)dx^2 - (1 - h_+)dy^2 - dz^2 \tag{2}$$

where,

$$h_+ = A_+ \, e^{i(k_g z - \omega_g t)}, h_\times = i A_\times \, e^{i(k_g z - \omega_g t)}, \tag{3}$$

A_+ and $A_\times$ are the constant GW amplitudes. In the linear order, the two polarization modes evolve independently. The characteristic strain (h) for exotic compact objects, with compactness C, is [10]:

$$h \lesssim 10^{-19} C^{5/2} \left(\frac{\rm MHz}{\omega_g}\right) \left(\frac{\rm Mpc}{D}\right) .$$

This translates to

$$h_{\rm 1.4GHz,10kpc} \lesssim 10^{-21} \, , h_{\rm 1.4GHz,1Mpc} \lesssim 10^{-23} \ .$$

In our model, we assume the GW amplitude h at the NS magnetosphere (at 10 kpc distance) to be 10^{-23} which is two orders of magnitude *lower than* the above-estimated amplitude.

NS generally has a dipolar magnetic field and is likely surrounded by a magnetosphere free from other forces [38]. At any point in the magnetosphere, we approximate the magnetic field by a constant value [39]. The effective time-dependent transverse magnetic field at a given point in the NS magnetosphere is given by

$$\mathbf{B}(t) = \left(0, B_y^{(0)} + \delta B_y \sin(\omega_B t), 0\right) \tag{4}$$

where ω_B is the frequency alternating magnetic field, which is equal to the frequency of rotation of NS (with $\omega_B \ll \omega_g$) [40]. The small time-dependence arises due to the rotation of the NS about its axis with frequency ω_B [27, 40, 41]. We consider ω_B in the range $[1, 10^3]$ Hz [38]. Note that $\xi \equiv \delta B_y / B_y^{(0)}$ can be as large as 0.1 [40]. We assume $\xi \sim 10^{-2}$.

To evaluate the transmutation of GWs to EM waves, we need to solve the covariant Maxwell's equations in the background metric (2). At linear-order, the induced electric and magnetic fields are [39]:

$$\tilde{E}_x \simeq -\frac{A_+}{2} B_y^{(0)} \left(1 - \xi\, \omega_B t\ \right)\ e^{i(k_g z - \omega_g t)} \tag{5}$$

$$\tilde{B}_y \simeq -\frac{A_+}{4} B_y^{(0)} \left(1 + 2\xi\, \omega_g t\ \right) e^{i(k_g z - \omega_g t)}\,. \tag{6}$$

Since the incoming GWs are plane-polarized, the transmuted EM waves will also be plane-polarized and, will have the same frequency at resonance [35, 37].

A conversion factor ($\alpha_{\rm tot}$), or ratio of the energy density of EM waves to GWs, can be used to estimate the conversion efficiency. For the entire magnetosphere, we get [39]:

$$\alpha_{\rm tot} \simeq \frac{5\pi G |B_y^{(0)}|^2}{2c^2} \left[\frac{4}{15}\xi^2 \left[\frac{R_{\rm LC}}{c}\right]^2 + \frac{2\xi R_{\rm LC}}{5\omega_g c} + \frac{1}{\omega_g^2}\right]. \tag{7}$$

Having discussed the assumptions of the model, in the rest of this essay, we discuss the key predictions of the model and compare them with the observations. Spectral flux density is the key observed quantity in all the FRB catalogs [27–31]. This observed quantity is related to the theoretically evaluated Poynting vector per unit frequency [42]. The Poynting vector is well-defined for photons that travel from the source to the observer without any hindrance [42–45]. The Poynting vector estimated at a small angle (along the direction of the incoming gravitational waves) remains the same at the source and the detector. Thus, the energy flux carried by the induced EM waves is [39]:

$$S_z = \frac{c}{8\pi} \tilde{E}_x \times \tilde{B}_y^* \simeq \frac{A_+^2\, |B_y^{(0)}|^2\, c}{64\pi} \left[1 + 2\omega_g \xi \frac{R_{\rm LC}}{c} - 2\omega_g \omega_B \xi^2 \left(\frac{R_{\rm LC}}{c}\right)^2\right] \tag{8}$$

where $\tilde{B}_y^*$ is the complex conjugate of the induced magnetic field $\tilde{B}_y$.

As mentioned above, the Poynting vector per unit frequency is the spectral flux density that characterizes FRBs [27–30]. The table below contains numerical values predicted by our model for the three input parameters — ω_g (frequency of the incoming HFGW), $R_{\rm LC}$ (light cylinder radius that defines the magnetosphere), and $B_y^{(0)}$ (average magnetic field in the magnetosphere). We see that our model predicts a range of spectral flux density that can be as small as 0.1 Jy (for milli-second Pulsar) and can be as large as 10^{11} Jy (for Magnetar).

$R_{\rm LC}$ (cm)	$B_y^{(0)}$ (Gauss)	ω_g (MHz)	$\alpha_{\rm tot}$	$\rho_{\rm EM}$ (Jy cm^{-1} s Hz)	$\frac{S_z}{\omega_g}$ (Jy)
10^9	10^{15}	1	1.74×10^{-5}	4.65×10^{10}	9.95×10^{11}
10^9	10^{12}	500	1.72×10^{-11}	1.15×10^{10}	9.94×10^{5}
10^8	10^{11}	1400	1.72×10^{-15}	9.07×10^{6}	961.57
10^7	10^{10}	1400	1.72×10^{-19}	9.07×10^{2}	0.99
10^8	10^{9}	1400	1.72×10^{-19}	9.07×10^{2}	0.09

TABLE I. Numerical values of the total conversion factor ($\alpha_{\rm tot}$), energy density of EM waves ($\rho_{\rm EM}$), and spectral flux density (Poynting vector per unit frequency). The first two rows are for a typical Magnetar and the last three rows are for a typical NS.

This is the most important conclusion of this essay, regarding which we wish to emphasize the following points:

1. From the last column of Table (I), we see that our model predicts the burst of EM wave with the flux < 1000 Jy. Our model predicts that the progenitor should be a NS with an effective magnetic field strength in the range $10^9 - 10^{11}$ G and rotation frequency $1 < \omega_B < 1000$. Thus, our model explains the observed peak flux of 99% of the reported FRBs [27–31].

2. It is estimated that around $10^8 - 10^9$ NSs are present in any given galaxy like the Milky Way, roughly 1% of the total number of stars in the galaxy [46, 47]. Also, it is estimated that the magnetar formation rate is approximately $1 - 10$ percent of all pulsars [48, 49]. Since Magnetars are rare, our model predicts that observing such a large spectral flux density is unlikely.

3. One of the fundamental assumptions of our model is that, given a GW signal in the

GHz frequency range, all NSs always act as FRB sources. This assumption means the maximum FRB events per day can be $10^8 - 10^9$. However, the observed FRB rate is 10^3 for the entire sky per day. This can be attributed to the fact that the probability of this event is a product of the probability that the GW passes through the NS times the probability that the emitted EM is along the line of sight of the observer.

4. $R_{\rm LC}$ for a typical NS is $\sim 10^7 - 10^9$ cm, implying that the GWs take less than one second to cover the entire magnetosphere [38]. This implies that the induced EM waves due to the GZ effect will appear as a burst lasting for less than one second. Thus, our model provides a natural explanation for the pulse width (lasting less than a second) of FRBs.

5. Since the incoming GWs are coherent, the induced EM waves will also be coherent. Thus, our model also explains the coherent nature of FRBs.

There is growing evidence for the existence of HFGWs ranging from MHz to GHz. Our results indicate that FRBs can be the smoking gun for the existence of HFGWs. As we just showed, in this model, the observed FRBs are due to the transmutation of GWaves to EM waves in the GHz range. Since the GZ mechanism has no complex physics, FRBs can provide key information about the sources emitting GWs in the GHz. Thus, a century after General Relativity, GWs with disparate frequencies can provide a distinct perspective of the cosmos, which can help to resolve some of the long-standing problems in cosmology and astrophysics. *Time will tell.*

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