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Gravitational Wave: Planetary Method for Detecting High-Frequency Gravitational Waves

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ABSTRACT

The detection of high-frequency gravitational waves (GWs) poses significant challenges in astrophysics, with current capabilities such as LIGO and Virgo limited to frequencies up to approximately 10 kilohertz. This frequency range excludes signals emitted by extreme dense astronomical objects and cosmological events from the very early universe, such as primordial black holes, boson stars, or phase transitions and inflation, which preserves the mystery of those astrophysical phenomena. This paper introduces a new method for detecting high-frequency gravitational waves (HFGWs) that utilizes the planetary magnetosphere, a concept inspired by the inverse Gertsenshtein Effect. Through the magnetosphere of planets like Earth and Jupiter, this method proposes converting gravitational waves into signal photons, potentially capturing signals that have hitherto remained beyond the reach of existing ground-based detectors. The theoretical foundation and potential implications of this approach, as proposed in Liu et al. (2024), suggest a promising new method for gravitational wave astronomy, opening the door to observations that could reshape our understanding of the universe's most elusive phenomena.

1. INTRODUCTION

Gravitational waves (GWs), first predicted by Einstein (1916) in 1916 as a consequence of his General Theory of Relativity, represent oscillations in the spacetime caused by some of the most violent and energetic processes in the Universe. These waves were detected directly for the first time a century later by the Laser Interferometer Gravitational-Wave Observatory (LIGO), a milestone that opened new method for astronomical observation and verified prediction of the Einstein.

Although ground-based detectors already has a fairly sensitive detector, current gravitational wave observatories such as LIGO and Virgo are primarily sensitive to low to mid-frequency gravitational waves, typically ranging up to around 10 kilohertz. This frequency range restricts our observational capabilities to certain types of astronomical events and objects, leaving high-frequency gravitational waves (HFGWs) largely unexplored. HFGWs are theorized to emit from extremely dense and compact objects, such as primordial black holes, boson stars, or events like phase transitions and inflation in the very early universe. The detection of these waves could provide significant insights into the early moments of the universe and offer clues about the fundamental laws and rules of physics that govern it which might beyond the standard model we have.

However, the challenge of detecting HFGWs lies in their extremely high frequencies, which require detection methods beyond the capacity of existing ground-based detectors. This paper proposes a new detection method that utilizes the planetary magnetosphere, specifically utilizing the inverse Gertsenshtein Effect. By measuring the conversion probability produced by GFGWs, this method is intended to explore high-frequency gravitational waves that are currently slightly observed, which could offer us a more complete view of the universe.

2. GRAVITATIONAL WAVES

Gravitational waves are ripples (see Figure 1) in the spacetime that propagate at the speed of light, generated by some of the most "cataclysmic" events in the universe. Predicted by Albert Einstein (1916) in his general theory of relativity, gravitational waves are produced by asymmetric accelerations of massive bodies, such as the collision of black holes, neutron stars, or other large celestial phenomena.

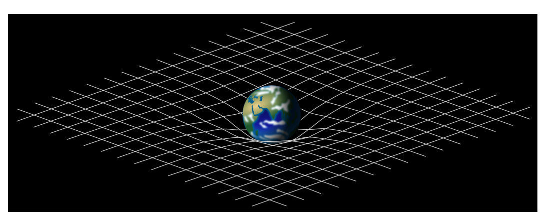

Figure 1: Spacetime Curvature Schematic made by Mysid

The propagation of these waves carries with it information about their origins and about the nature of gravity itself, offering a unique insight into the hidden areas of the universe that are otherwise obscured from view by interstellar dust or electromagnetic interference. Unlike electromagnetic waves, which can be absorbed or reflected by matter, gravitational waves pass through matter unimpeded, providing an unchanged view of their source events.

The value of gravitational waves lies not only in their ability to inform us about events taking place billions of light years away but also in their potential to expand our understanding of the fundamental laws of physics. They offer a direct means to observe and study phenomena such as black holes and neutron stars—objects that are otherwise nearly impossible to detect—thus opening a new window into astrophysics, cosmology, and the very structure of the cosmos.

The direct detection of gravitational waves, however, is a monumental challenge due to their incredibly weak effect on matter. The historic first direct detection by LIGO (Abbott et al. (2016)) in September 2015 confirmed Einstein's predictions and marked the beginning of gravitational wave astronomy. This detection of gravitational waves from a pair of merging black holes opened up a new era in observational astronomy, providing the first glimpses of the violent cosmos from which gravitational waves emit.

By understanding gravitational waves, scientists hope to gain new insights into the early universe—moments after the Big Bang—where these waves hold the potential to provide information about processes and phenomena that are invisible by any other method. Thus, gravitational waves not only challenge our existing knowledge and technology but also hold the promise to fundamentally alter our understanding of the universe.

3. THE LIMITATION OF LASER INTERFEROMETERS

Current ground-based detectors are designed to detect gravitational waves within a frequency range of approximately 10 Hz to 10 kHz. In theory, gravitational waves (GWs) can be emitted at any frequency, potentially extending below or above the standard detection range. Currently, the space-based laser interferometer, the Space Antenna (LISA) (Amaro-Seoane et al. (2017)), targets the lower frequency spectrum, covering from 0.1 to 10 mHz. However, detectors specifically designed for frequencies above 10 kHz are notably scarce.

The frequency range detectable by a laser interferometer is primarily determined by its arm length; longer arms are advantageous primarily when the wavelength of the gravitational waves (GWs) exceeds the length of the interferometer arms. The satellite-based detector LISA achieves sensitivity to lower GW frequencies by extending its arm length, which additionally helps minimize the impact of environmental noise, such as seismic disturbances. For HFGWs, or gravitational waves with shorter wavelengths, the shorter arm lengths of laser interferometers limit the achievable strain sensitivity, thereby constraining the upper frequency limit that these instruments can detect when it used as a direct strain meter.

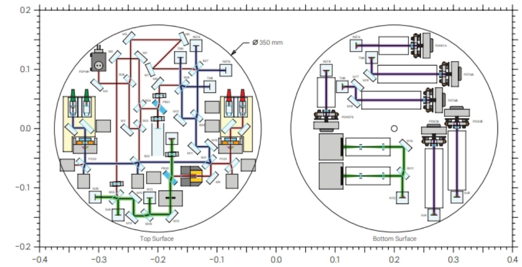

Figure 2: Possible Layout of the optical bench for LISA (Amaro-Seoane et al. (2017), Figure 7)

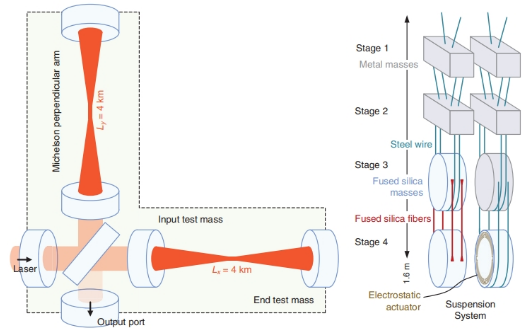

Figure 3: Interferometer configuration and test mass setup (Abbott et al. (2016), Figure 2)

4. THE INVERSE GERTSENSHTEIN EFFECT

Direct detection of GWs is inherently difficult due to their extremely weak nature, which causes only minuscule disturbances in spacetime—often to the extent that they are barely measurable. Devices like interferometers are typically used to directly measure these tiny vibrations, but only those emanating from the most cataclysmic events, such as mergers between black holes and neutron stars. However, GWs can also be detected indirectly by observing their effects on other systems or by identifying phenomena that arise as a result of these waves. One notable example of such an indirect detection method is the inverse Gertsenshtein effect.

The Gertsenshtein effect, first introduced by physicist Gertsenshtein in 1961, describes how photons (the carriers of electromagnetic forces) can be converted into gravitons (theoretical particles believed to mediate gravitational forces) in the presence of a magnetic field. Conversely, the inverse Gertsenshtein effect details how gravitons can be converted back into photons, effectively transforming gravitational waves (GWs) into electromagnetic (EM) waves, or light, as depicted in Figure 4 (from left to right).

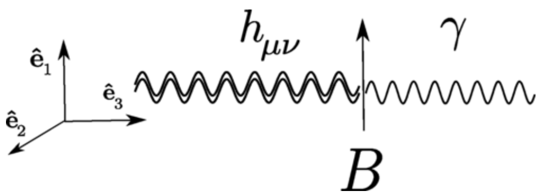

Figure 4: The Gertsenshtein Effect (Domcke & Garcia-Cely (2021), figure 1)

Electromagnetic waves across a broad spectrum of frequencies are well-understood and extensively studied, making them readily detectable through numerous experimental techniques. Given our advanced sensitivity to EM waves, particularly at high frequencies, the inverse Gertsenshtein effect provides a pathway to detecting high-frequency GWs. Although initially thought to be too weak to be practically observable, the interaction required to observe this effect would necessitate an extraordinarily large magnetic field. Such fields, however, are naturally found in planetary magnetospheres, presenting a unique opportunity for detection.

5. PLANETARY METHOD

A magnetosphere encompasses the area around a planet where its magnetic field is the dominant force. The substantial magnetic fields of both Earth and Jupiter enhance the likelihood of the inverse Gertsenshtein effect occurring, making it feasible for detection purposes. Consequently, these planetary magnetospheres serve as effective laboratories for the detection of HFGWs.

This detection method relies on measuring the photons generated from GWs through the inverse Gertsenshtein Effect within a planetary magnetosphere. The likelihood that a GW passing through a magnetic field will transform into a photon or electromagnetic (EM) wave is termed the conversion probability. This probability is a critical metric for this method, as it quantifies the effectiveness of the magnetosphere in facilitating this conversion.

With a WKB approximation, the inverse Gertsenshtein effect is described by a mixing matrix (Raffelt & Stodolsky (1988))

$$\begin{pmatrix} \Delta_\gamma & \Delta_M \\ \Delta_M & 0 \end{pmatrix} \tag{1}$$

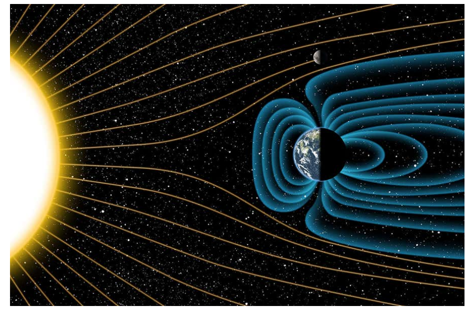

Figure 5: Artistic illustration of Earth's magnetosphere (blue), which protects us from solar radiation (yellow). (Graphic by Michael Osadciw)

where $\Delta_M = \frac{1}{2}\kappa B_t$ represents the mixing between GWs and photons, where $\kappa = (16\pi G)^{1/2}$ and B_t denotes the component of the external magnetic field $\mathbb{B}$ that is transverse to the direction of the GW's propagation. The effective photon mass is denoted by $\Delta_\gamma \approx \Delta_{\rm vac} + \Delta_{\rm pla}$. Here, $\Delta_{\rm vac} = 7\alpha\omega/(90\pi)\left(\frac{B_t}{B_c}\right)^2$ represents the quantum electrodynamics (QED) vacuum effect, with α as the fine-structure constant, ω the angular frequency, and $B_c = m_e^2/e$ the critical magnetic field. $\Delta_{\rm pla} = -\frac{m_{\rm pla}^2}{2\omega}$ accounts for the plasma mass contribution, where $m_{\rm pla}^2 = 4\pi\alpha n_c/m_c$, with n_c and m_c being the number density and invariant mass of the charged plasma particles, respectively. By diagonalizing this mixing matrix, the GW-photon conversion probability in a homogeneous magnetic field can be determined:

$$P = \sin^2(2\Theta)\sin^2\left(\frac{L}{l_{\rm osc}}\right) = (\Delta_M L)^2 \sin c^2\left(\frac{L}{l_{\rm osc}}\right) \tag{2}$$

Here $\Theta = 1/2\arcsin(\Delta_M l_{\rm osc})$ and $l_{\rm osc} = 2/(4\Delta_M^2 + \Delta_\gamma^2)^{1/2}$ are the GW-photon mixing angle and oscillation length, respectively. L represents the travel distance of GWs in the magnetic field.

Followed by the instructions of Liu et al. (2024), considering a satellite-based detector located at altitude H and latitude $\lambda_{O'}$, and define its instant spherical coordinate system with $\hat{z}'$ pointing to the planet's center (see Figure 6). Based on this assumption, we could be able to evaluate $P(\Omega')$ of HFGWs traveling to this detector in all directions, where $\Omega' = \{\theta', \phi'\}$.

The detection efficiency of the GW to photon conversion by a detector varies with direction, denoted as

Table 1: Benchmark scenarios for sensitivity study. See details in Liu et al. (2024) Table I.

	Satellite orbit				Detector Properties				
	H (km)	θ_{inc}	T_{dark} (s)		IR	UV-Optical	EUV	X-ray	γ-ray
Conservative	600	31.4°	10^7	$\Delta\Omega$(sr)	1.6×10^{-2}	10^{-6}	10^{-5}	3×10^{-5}	2.4
				A (cm^2)	0.1225	4.5×10^4	1	250	8000
Optimistic	800	98°	10^8	$\Delta\Omega$(sr)	3.4	3.4	3.4	3.4	3.4
				A (cm^2)	0.1	10^2	10^2	10^2	10^4

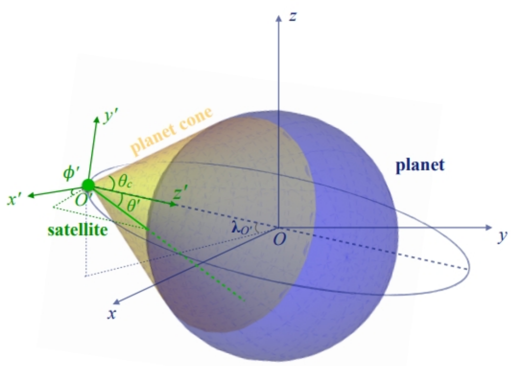

Figure 6: Instant coordinate system for a satellite-based detector. (From Liu et al. (2024) supplemental materials, Figure S4)

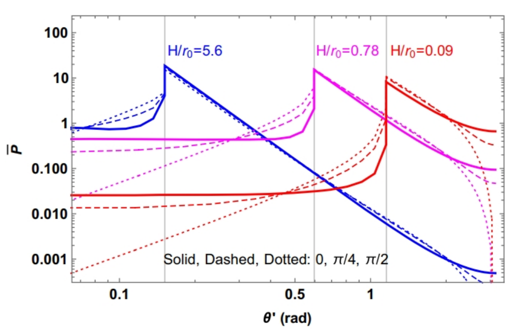

Figure 7: $\bar{P}(\theta')$ as a function of θ' for a satellite-based detector, with $f = 10^8$ GHz. The color and line style denote the normalized altitude H/r_0 and the latitudes $\lambda_{O'}$ respectively for the satellite. The vertical lines denote θ_c for the PC with different H/r_0 values (From Liu et al. (2024), Figure 2).

$\Omega' = \{\theta', \phi'\}$. Figure 2 illustrates the θ' dependence of the conversion probability $P(\Omega')$, with the angle-averaged probability $\bar{P}(\theta')$ defined as

$$\bar{P}(\theta') = (2\pi P_0)^{-1} \int_0^{2\pi} P(\Omega') d\phi' \tag{3}$$

While Figure 7 is depicted for a frequency of $f = 10^8$ GHz, the characteristics it exhibits remain largely consistent across the gravitational wave (GW) frequency spectrum of interest. In this analysis, the impact of plasma is assumed to be negligible. The directions from which photons arrive are categorized into two regions: the planet-cone (PC) for $\theta' < \theta_c = \arcsin\left[\frac{r_0}{r_0+H}\right]$, and the outer-space (OS) for $\theta' > \theta_c$, determined by whether the photons' trajectories intersect the planetary surface. For all parameter combinations $(H/r_0, \lambda'_0)$, the averaged conversion probability $\bar{P}(\theta')$ exhibits a pronounced peak at the boundary of the PC and declines steeply beyond this region. At $\lambda'_0 = \pi/2$, the probability diminishes to zero at $\theta' = 0$, correlating with the disappearance of the transverse magnetic field component B_t in this orientation, particularly for a detector positioned directly over the planetary poles. As the ratio H/r_0 increases, leading to a reduced PC area, $\bar{P}(\theta')$ correspondingly increases within the PC, attributable to the extended path of GW-photon conversion.

Stochastic gravitational waves are generally isotropic and maintain a constant state. Within the context of a detector located in the planetary magnetosphere, the flux of photons converted from gravitational waves is described as follows (refer to Leroy et al. (2020) for details).

$$\Phi_\gamma = \int_{\Delta\Omega} d\Omega' \int d\omega \frac{1}{\omega} \frac{d}{d\omega} \frac{d\rho_{\text{GW}}}{d\Omega} P(\Omega') \tag{4}$$

The symbol Ω represents the detector's field of view (FOV). The differential energy density of gravitational waves per solid angle and logarithmic frequency interval is given by $d\rho_{\text{GW}}/d\Omega d\ln\omega = \omega^2 h_c^2/(4\pi\kappa^2)$, where h_c denotes the characteristic strain of the gravitational wave. It's important to note that the distribution of photons converted from gravitational waves in angular terms is specified by $P(\Omega')$, and only those photons that enter the detector's FOV contribute to the photon flux ϕ_γ. For a defined frequency band $\Delta\omega$, a limited time period Δt, and a specified effective area of the detector A, the counts for both signal and background can consequently be determined:

$$s \approx \Phi_\gamma A \Delta t \approx \frac{h_c^2}{4\pi\kappa^2} \langle P \rangle_{\rm det} A \Delta t \Delta\omega \Delta\Omega, \qquad (5)$$

$$b \approx \Phi_b A \Delta t \approx \phi_b A \Delta t \Delta\omega \Delta\Omega. \qquad (6)$$

Here, the average GW-photon conversion probability over the field of view (FOV) of the detector, denoted by $\langle P \rangle_{\rm det}$, is defined as

$$\langle P \rangle_{\rm det} = \frac{\int_{\Delta\Omega} P(\Omega') d\Omega'}{\Delta\Omega} \qquad (7)$$

which is fundamentally determined by the detector's position and its pointing direction $\{\theta'_{\rm det}, \phi'_{\rm det}\}$. Specifically, if the detector is aligned with the planet's center ($\theta'_{\rm det} = 0$), $\langle P \rangle_{\rm det}$ is proportional to

$$\frac{\int_{\Delta\Omega} \bar{P}(\theta') \sin\theta' d\theta'}{\int_{\Delta\Omega} \sin\theta' d\theta'} \qquad (8)$$

and this value increases with the solid angle $\Delta\Omega$ within the planet-cone (PC). The 95% confidence level upper limit on the characteristic strain h_c can be inferred from the ratio $s/\sqrt{b} \approx 1.64$ in the context of a significant background limit, as described by the equation:

$$h_{c,95\%} \approx 4.5\kappa \left(\frac{\phi_b}{A \Delta t \Delta\omega \Delta\Omega} \right)^{1/4} \left(\frac{1}{\langle P \rangle_{\rm det}} \right)^{1/2}. \qquad (9)$$

Under this simplified model (assuming a uniform background flux ϕ_b), Liu et al. (2024) define two benchmark scenarios, named "conservative" and "optimistic", in table 1. Figure 8 presents the projected 95% confidence level (CL) constraints on the characteristic strain of HFGWs across a broad range of frequencies, encompassing a significant portion previously unexplored. With such a high frequency detection range, this method may make it possible to observe previously undetectable objects and cosmic events.

6. CONCLUSION

In this paper, we have outlined a method of Liu et al. (2024) to detect stochastic high-frequency gravitational waves (HFGWs) within the planetary magnetosphere. The approach is built on the relatively long pathway of effective GW-photon conversion, coupled with a broad angular distribution of the signal flux and comprehensive coverage across the electromagnetic (EM) observational frequency band used in astronomy. This method provide a new platform for astronomers to observe the universe.

Should the methodologies described herein be applied in the future, alongside current detectors focus on lower and mid-range gravitational wave frequencies like LIGO and LISA, we stand to cumulative a more comprehensive array of gravitational wave observations spanning a broader range of frequencies. This advancement could markedly enhance our capacity to investigate the distant cosmos and the universe's nascent epochs. Such explorations hold the potential to refine, and perhaps fundamentally alter, our prevailing standard model of particle physics—an endeavor that is profoundly stimulating.

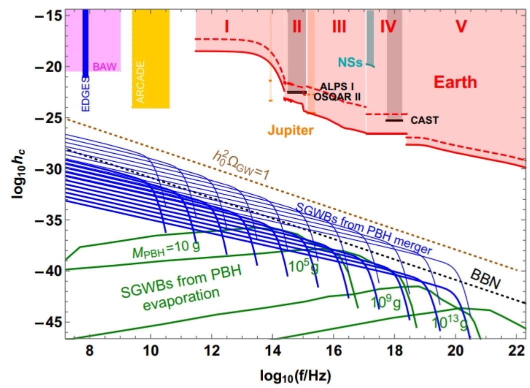

Figure 8: Projected 95% C.L. upper limits on the characteristic strain h_c of stochastic HFGWs, set by the LEO satellites (red). (From Liu et al. (2024), Figure 3)

APPENDIX

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