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Abstract

In electromagnetic environments, binary black hole mergers can radiate electromagnetic signals at frequencies identical to gravitational waves; however, low-frequency electromagnetic waves may be absorbed by the interstellar medium. During atmospheric propagation, electromagnetic waves experience frequency-dependent absorption, with certain frequencies attenuated more strongly than others. Those frequency windows subject to weaker absorption are designated as atmospheric windows for electromagnetic waves. Analogously, electromagnetic waves propagating through cosmic space may be absorbed by the interstellar medium. This investigation focuses specifically on the absorption of electromagnetic waves traversing the interstellar medium of the Milky Way. Research reveals that electromagnetic waves propagating through Milky Way space to reach Earth are subject to a lower cutoff frequency. The corresponding lower cutoff frequencies vary across different directions on the celestial sphere, exhibiting a distribution intimately correlated with the distribution of free electron gas in the Milky Way. This paper determines the distribution of free electron gas in the Milky Way through measurement of this cutoff frequency distribution.

Full Text

Preamble

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Very Low Frequency Electromagnetic Wave Absorption and Free Electron Gas Distribution in the Milky Way

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Abstract

Electromagnetic waves are absorbed when passing through Earth's atmosphere, with certain frequencies experiencing greater attenuation than others. The frequency ranges that suffer minimal absorption form what we call atmospheric windows. Analogously, electromagnetic waves propagating through cosmic space are absorbed by the intergalactic medium. This paper investigates the absorption of electromagnetic waves as they travel through the Milky Way. Our analysis reveals the existence of a lower cutoff frequency for electromagnetic waves that can traverse the Galaxy and reach Earth. Notably, this lower cutoff frequency varies across different directions on the celestial sphere, forming a distinct distribution that is intimately related to the distribution of free electron gas in the Milky Way. We propose that by measuring this cutoff frequency distribution, we can determine the distribution of free electron gas throughout our Galaxy.

Keywords: electromagnetic wave; free electron gas; cutoff frequency

1 Introduction

Since the first detection of gravitational waves by the LIGO detector in September 2015, over one hundred gravitational wave events have been observed. Gravitational wave astronomy has been established as a new observational paradigm and is developing at a remarkable pace. Multi-messenger astronomy, which combines gravitational wave and electromagnetic observations, has garnered significant attention. The August 2017 binary neutron star merger event serves as a prime example, where joint gravitational and electromagnetic observations simultaneously resolved three major astrophysical questions: the central engine of short gamma-ray bursts, the kilonova mechanism, and the origin of heavy elements. This demonstrates the extraordinary scientific potential of combined gravitational and electromagnetic observations.

To date, the binary neutron star merger remains our only example of such joint observations. The question of whether astrophysical black holes carry electric charge, and if so, how much, has been a topic of intense recent debate. Mergers of charged binary black holes and black hole binaries in magnetic environments can produce electromagnetic signals at frequencies comparable to their gravitational wave counterparts. For instance, ground-based detectors like LIGO observe gravitational waves at frequencies of hundreds of hertz, future space-based detectors will operate at millihertz frequencies, and pulsar timing arrays probe nanohertz frequencies. In contrast, current electromagnetic observations rarely explore frequencies below 10 MHz, with typical radio astronomy conducted in the gigahertz regime.

There are two primary reasons why electromagnetic observations below 10 MHz have been neglected: first, whether astrophysically significant sources emit at these very low frequencies remains unclear; and second, whether such waves can propagate through cosmic space without being completely absorbed is uncertain. The first consideration is no longer a concern, as strong scientific motivation now exists to search for sub-10 MHz signals. The second issue forms the central focus of this paper.

The absorption of electromagnetic waves by Earth's atmosphere is a well-understood phenomenon, where different atmospheric molecules absorb specific frequencies to varying degrees, creating the familiar atmospheric transmission windows. While not perfectly transparent, we possess comprehensive knowledge of absorption coefficients across frequencies. Cosmic space is nearly vacuum but contains trace amounts of interstellar medium, predominantly composed of free electron gas—or more precisely, plasma consisting of free electrons and ions. The plasma absorption mechanism differs fundamentally from molecular absorption. In Section 2, we review the theory of plasma-electromagnetic wave interactions and the underlying absorption mechanism. Section 3 applies this mechanism to the Milky Way's interstellar medium, analyzing how galactic free electron gas distribution affects electromagnetic wave absorption. Finally, Section 4 summarizes our findings and proposes a method to determine the free electron gas distribution by measuring the absorption characteristics.

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2 Plasma-Electromagnetic Wave Interactions

Electromagnetic wave propagation in a medium is governed by Maxwell's equations:

$$\begin{aligned} \nabla \cdot (\epsilon \mathbf{E}) &= \rho, \\ \nabla \cdot \mathbf{B} &= 0, \\ \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t}, \\ \nabla \times \mathbf{B} &= \mathbf{j} + \frac{\partial (\epsilon \mathbf{E})}{\partial t}, \end{aligned}$$

where ρ is the free charge density, $\mathbf{j}$ is the conduction current density, ϵ and μ are the medium's permittivity and permeability, and $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields.

For free electron gas, ϵ and μ can be approximated as:

$$\mu \approx \mu_0, \quad \epsilon \approx \epsilon_0 \left(1 - \frac{\omega_p^2}{\omega^2}\right),$$

where ϵ_0 and μ_0 are the vacuum permittivity and permeability, ω is the electromagnetic wave frequency, and ω_p is the plasma frequency:

$$\omega_p^2 = \frac{ne^2}{m\epsilon_0},$$

with n being the electron number density, e the electron charge, and m the electron mass. Since n varies spatially, ϵ becomes a function of position while μ remains essentially constant.

Given constant μ and spatially varying ϵ, Maxwell's equations simplify to:

$$\frac{\partial^2 \mathbf{E}}{\partial t^2} + \nabla^2 \mathbf{E} + \nabla \left(\frac{\nabla \epsilon}{\epsilon} \cdot \mathbf{E}\right) = 0.$$

For monochromatic waves, $\mathbf{E} = \mathbf{E}_0 e^{i(\omega t - \mathbf{k} \cdot \mathbf{r})}$, yielding the modified Helmholtz equation:

$$\omega^2 \epsilon \mu \mathbf{E} + \nabla^2 \mathbf{E} + \nabla \left(\frac{\nabla \epsilon}{\epsilon} \cdot \mathbf{E}\right) = 0.$$

Interstellar free electron gas density varies slowly, with characteristic scales exceeding 0.001 pc. By dividing the region between source and detector into subregions smaller than this variation scale, we can approximate n as constant within each subregion. Equation (9) then reduces to the standard Helmholtz equation:

$$\omega^2 \epsilon \mu \mathbf{E} + \nabla^2 \mathbf{E} = 0.$$

Restricting our analysis to the propagation direction from the source and denoting this direction as x, we obtain:

$$\omega^2 \epsilon \mu E + \frac{\partial^2 E}{\partial x^2} = 0.$$

Let E_i and E_{i+1} represent the electric field before entering and after exiting the i-th subregion (equivalently, before entering the $(i+1)$-th subregion). Solving Equation (11) yields:

$$E_{i+1} = E_i e^{ik\delta x}, \quad k = \omega\sqrt{\epsilon\mu},$$

where δx is the thickness of the i-th subregion along x. Propagating through all subregions gives the relationship between the detector field E_d and source field E_s:

$$E_d = E_s \exp\left(i \int k\, dx\right),$$

with the integral evaluated from source to detector. If the integral $\int k\, dx$ has an imaginary part I, the wave intensity attenuates by a factor of e^{2I} due to absorption.

Applying this framework to propagation from the Milky Way's edge to Earth reveals the absorption of electromagnetic waves by the Galaxy's interstellar medium. If $\int k\, dx$ is purely real, no absorption occurs; conversely, an imaginary component indicates absorption.

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3 Absorption by the Milky Way's Interstellar Medium

Analogous to atmospheric absorption, we define the Milky Way's interstellar medium absorption coefficient as:

$$\xi(\omega, \theta, \phi) = 1 - e^{-2\Im[\int k\, dx]},$$

where the integral proceeds from Earth to the Milky Way's edge along the celestial direction (θ, ϕ), and $\Im$ denotes the imaginary part. Our coordinate system places the origin at the Sun, with the galactic plane as the xy-plane and the Sun-Galactic Center line as the x-axis. Though this rotating frame completes one revolution every 220 million years, the rotation is sufficiently slow for our purposes.

The absorption coefficient $\xi(\omega, \theta, \phi)$ exhibits a step-function behavior with respect to frequency. As illustrated in Figure 1 [Figure 1: see original paper] for an arbitrary direction, there exists a cutoff frequency f_l for each line of sight. Electromagnetic waves with frequencies above f_l propagate through the interstellar medium unattenuated, while those below f_l are completely absorbed.

Note: Calculations are based on the YMW16 free electron gas distribution model.

Figure 1 Absorption coefficient of the Milky Way's interstellar medium as a function of electromagnetic wave frequency.

The Milky Way's interstellar medium consists primarily of free electron gas. Several researchers have developed detailed models of the galactic free electron distribution, notably the TC93 model by Taylor and Cordes. Building upon earlier axisymmetric assumptions, TC93 incorporated correlations between spiral arm positions and pulsar distributions while accounting for dispersion from Gum Nebulae, achieving ~25% distance accuracy for known pulsars. However, TC93 underestimates densities at high galactic latitudes, yields only lower distance limits, and contains significant errors in spiral arm electron distributions.

Cordes and Lazio subsequently developed the NE2001 model, incorporating additional measurements and improved constraints on galactic center scattering. They divided the Galaxy into thick disk, thin disk, and spiral arm components, employing an iterative likelihood method to determine optimal parameters. NE2001's accuracy degrades at high latitudes, where it underestimates observed values.

Yao et al. advanced this work with the YMW16 model, partitioning the Galaxy into seven components: thick disk, thin disk, spiral arms, galactic center, local bubble, and loop regions. YMW16 accounts for contributions from multiple regions at component boundaries and outperforms NE2001 by nearly 40% within 95% confidence intervals.

Using the YMW16 model, Figure 2a [Figure 2: see original paper] presents the cutoff frequency distribution across the celestial sphere. The cutoff frequencies range from 5×10^3 to 1.1×10^4 Hz, with elevated values corresponding to loop region directions. For comparison, Figure 2b shows the distribution based on the NE2001 model, revealing significant differences between the two electron gas models.

Note: (a) Based on the YMW16 free electron gas distribution model; (b) Based on the NE2001 free electron gas distribution model.

Figure 2 Distribution of cutoff frequencies for electromagnetic waves propagating through the Milky Way's interstellar medium to Earth.

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4 Summary and Discussion

Due to absorption by the Milky Way's interstellar medium, electromagnetic waves below 1000 Hz cannot traverse the Galaxy to reach Earth. Consequently, astronomical electromagnetic signals at these frequencies are unobservable. This implies that detecting electromagnetic counterparts from merging charged stellar-mass black holes in magnetic environments is not feasible. However, radio and higher-frequency electromagnetic signals produced through other mechanisms during black hole mergers remain viable observational targets.

Charged or magnetized stellar-mass binary black holes generate very low frequency electromagnetic waves in the 300 Hz–3 kHz range, which cannot propagate through the interstellar medium. Our study indicates that waves above 5000 Hz can travel through interstellar space. Primordial black holes with masses below $1M_\odot$ could produce very low frequency waves in the 3×10^3–3×10^4 Hz range under charged or magnetized conditions, enabling them to reach Earth.

Superconducting Quantum Interference Devices (SQUIDs) and resonant cold coil technologies can detect such weak very low frequency signals. SQUIDs, based on the Josephson effect and magnetic flux quantization, exhibit exceptional sensitivity to magnetic field components in this frequency range. Domestically developed SQUIDs in China have achieved magnetic field sensitivity of 10^{-15} T, enabling their use in space physics experiments such as Gravity Probe B and dark matter searches.

The Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, has begun precision measurements of very low frequency signals in Earth's atmospheric environment using SQUIDs. We anticipate that future SQUID observations will enable measurement and mapping of the cutoff frequency distribution across the celestial sphere, providing a powerful tool to discriminate between and validate different models of the Milky Way's free electron gas distribution.

References

[1] Abbott B P, Abbott R, Abbott T D, et al. Physical Review Letters, 2016, 116: 1102

[2] Abbott R, Abbott T D, Acernese F, et al. arXiv:2111.03606, 2021

[3] CAO Zhou-jian. Modern Physics, 2015, 27(5): 40

[4] CAI Rong-gen, CAO Zhou-jian, HAN Wen-biao. Science Bulletin, 2016, 61(14): 1525

[5] CAO Zhou-jian, DU Zhi-hui. Science China, 2017, 47(1): 0405

[6] CAO Zhou-jian, HE Xiao-kai. Science China, 2018, 48(7): 9806

[7] YAN Wei-chen, ZHAO Tian-yu, CAO Zhou-jian. Progress in Astronomy, 2019, 37(4): 469

[8] HE Xiao-kai, CAO Zhou-jian, LIANG Can-bin. College Physics, 2019, 38(5): 1

[9] LIU Gang-qiang, CAO Zhou-jian. Progress in Astronomy, 2021, 39(1): 94

[10] CAO Zhou-jian. College Physics, 2018, 37(2): 1

[11] Zhang B. Astrophys J, 2016, 827: L31
[12] Gong Y, Cao Z, Gao H, et al. MNRAS, 2019, 488: 2722
[13] Zilhao M, Cardoso V, Herdeiro C, et al. Physical Review D, 2012, 85: 4062
[14] Bozzola G, Paschalidis V. Physical Review Letters, 2021, 126: 1103
[15] Palenzuela C, Anderson M, Lehner L, et al. Physical Review Letters, 2009, 103: 1101
[16] Palenzuela C, Lehner L, Liebling S L. Science, 2010, 329: 927
[17] Bogdanovic T, Miller M C, Blecha L. Living Review in Relativity, 2022, 25: 3
[18] Jackson J D. Classical Electrodynamics, 3rd Edition. New York: Wiley Press, 1998: 309
[19] Taylor J H, Cordes J M. The Astrophysical Journal, 1993, 411: 674
[20] Cordes J M, Lazio T J W. arXiv:astro-ph/0207156, 2023
[21] Cordes J M, Lazio T J W. arXiv:astro-ph/0301598, 2023
[22] Yao J, Manchester R N, Wang N. ApJ, 2017, 835: 29
[23] Benavides-Gallego C, Han W B. Symmetry, 2023, 15: 537
[24] Benavides-Gallego C, Han W B. arXiv: 2111.04323, 2021
[25] Asztalos S J, Carosi G, Hagmann C, et al. Physical Review Letters, 2010, 104: 041301
[26] Range S K. Gravity Probe B: Exploring Einstein's Universe with Gyroscopes. US: NASA Educator's Guide, 2008: 26
[27] Hao H, Wang H, Chen Liu, et al. Sensors, 2017, 17: 371

Note: Figure translations are in progress. See original paper for figures.