High frequency gravitational waves from photon sphere of supermassive black holes

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論文内容の要旨

氏　名　　　齊藤　海秀

専　攻　　　物理学専攻

論文題目（外国語の場合は，その和訳を併記すること。）

High frequency gravitational waves from photon sphere of supermassive black holes

(超巨大ブラックホール光子球からの高周波重力波)

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Binary systems composed of the stellar-mass black hole(BH) and the neutron star radiate gravitational-waves(GWs) with a frequency of about $f_{\rm GW} \sim 10 - 10^3$ Hz. Aiming at this frequency range, ground-based laser interferometers such as LIGO were designed. When the first GWs from a binary stellar-mass BH were detected in 2015, it became possible to extract the physical information of compact stars from GWs. That was the dawn of the GW astronomy.

As the research of astronomy has been extended from optical to other multiwavelength, GWs with a frequency other than the frequency range of the LIGO have attracted much interest. In a low-frequency range, stochastic GWs from supermassive black hole(SMBH) binaries are reported. On the other hand, in a high-frequency range, there are interesting predictions of GWs from the beyond standard model and primordial black holes, etc.. Therefore, GWs not only provide information of compact stars but also give the opportunity of testing various unconfirmed physics. Thus, it is worth realizing multiwavelength GW observation in the future.

In this thesis, we focus on high-frequency GWs above 10^{14}Hz. As for the detection of GWs above 10^{14}Hz, we can use existing axion detectors. In axion detection, we utilize interaction between axion and photon. Under the existence of a background magnetic field, axion and photon are mixed, and we can detect optical and X-ray signals arising from the axion photon mixing by CCD camera. This is the idea of axion experiments such as the CERN Axion Solar Telescope(CAST). Meanwhile, in a background magnetic field, mixing between graviton also occurs, and it is possible to detect the GWs above 10^{14}Hz from space by converting it to visible light or X-ray as we do so in axion experiments. Reinterpreting the results of axion experiments such as CAST, A.Ejilli et al.(2019) excluded the high-frequency GW with $\sim 10^{18}$Hz down to $h \sim 10^{-27}$, where h is the amplitude of GWs. To summarize, for the GWs above 10^{14}Hz, one can utilize the existing data of axion experiments to constrain the GW amplitude.

For the further progress of detecting GWs above 10^{14}Hz, the existence of guaranteed sources is essential. However, to the best of my knowledge, except for the solar core, there are no guaranteed sources of GWs above 10^{14}Hz. Also, note that the GW amplitude from the solar core is not so large. In consideration of the above situation, it is natural to seek guaranteed sources for high-frequency GWs above 10^{14}Hz. In our research, we are aiming to propose a new guaranteed source of high-frequency GWs above 10^{14}Hz. Consequently, we proposed a new guaranteed source, namely a photon sphere of a supermassive black hole which steadily emits high-frequency GWs through the photon-graviton mixing(conversion). Assuming the hot accretion flow model, we find that the typical frequency of the GWs is $10^{19}-10^{20}$ Hz. Since the frequency of the GWs is not sensitive to the mass of the supermassive black hole, each signal cannot be resolved and forms stochastic GWs background with $10^{19}-10^{20}$ Hz. We find that its density parameter becomes $\Omega_{GW}\sim10^{-15}$ at the maximum. We also discuss the possible application of our graviton creation mechanism to other low-mass particle creation near the photon sphere of supermassive black holes.

The structure of the thesis is as follows:

・Chap.2(Review Part): Test Particle Motion around a BH

In this chapter, we discuss the trajectory of a freely moving test particle around the Schwarzschild black hole for both massive and massless cases. Section 2.1 summarizes the basics in preparation for the sections that follow. The definition of the action of a freely moving particle in an arbitrary spacetime, the definitions of the Schwarzschild coordinates, and the local observer's coordinates in the Schwarzschild spacetime were given. Section 2.2 describes the geodesics of a massive particle. Its effective potential as the function of the radial coordinate and the angular momentum is essential to understand the qualitative nature of the accretion disk as discussed in Chapter 3. Section 2.3 describes the geodesics of a massless particle. In this section, we introduce the unstable circular orbit of massless particles called the photon sphere. In order to estimate the conversion probability near the photon sphere of a BH, the propagation length(in other words the orbiting time around the photon sphere) is essential. In Section 2.4, we give the formula of orbiting time around the photon sphere of a BH.

・Chap.3(Review Part):　Accretion Onto Black Holes

In order to estimate the graviton production rate around the photon sphere, the magnetic field strength and plasma density around it are essential. These are determined by the accretion disk theory. In this chapter, we review the accretion disks from both observational and theoretical points of view. Firstly, in Section 3.1 we will observe the spectrum of the active galactic nuclei(AGNs) and summarize the features that accretion disk theory should reproduce. Section 3.2 provides a review of the oldest accretion disk model, the standard disk theory. It describes the radiatively efficient and cold accretion. A brief description of how accretion is caused by the viscosity is available in Subsection 3.2.1. In Section 3.3, we discuss the optically thin, hot accretion theory so-called ADAF. The ADAF account for the observed X-ray emission from AGNs. These two contrasting accretion disk theories discussed in Section 3.2 and Section 3.3 are expected to coexist in real AGNs. In Section 3.4, we introduce the hypothetical model that most simply describes their coexistence and see that it reproduces the observed spectra.

・Chap.4(Review Part): Photon Graviton Conversion

The aim of this Chapter is to derive the formula of conversion probability from photon to graviton. In Section 4.1, we define the effective action of the electromagnetic field in a curved spacetime and derive the Einstein equation and Maxwell equation. The action we define here is the so-called Euler-Heisenberg action in the flat spacetime case, which is the effective theory of the electromagnetic field that incorporates quantum effect due to electron one-loops. We also discuss the cutoff scale of the effective theory. In Section 4.2, we linearize the EoM obtained in Section 4.1. This leads to the coupled EoM for photon and graviton, which are essential for describing the photon graviton conversion. Note that in this section we consider the flat spacetime and an arbitrary background electromagnetic field. In Section 4.3, we write down the EoM for plane waves propagating in a transverse magnetic field. We decompose the linear EoM into each polarization. Since we are interested in high-energy photons whose wavelength is much shorter than the typical scale of variation of BHs, further simplification of EoM is possible by imposing the eikonal approximation. Section 4.4 implements this approximation. In Section 4.5, we explore the photon graviton conversion in the case of a uniform magnetic field with the EoM obtained in Section 4.4.. The formulae, which are essential to calculate the frequency and the luminosity of GWs from the photon sphere, are available in this section.

・Chap.5(Main chapter): High-frequency GWs from the Photon Sphere of SMBHs

The results of this chapter are based on our paper. In this Chapter, using the technique developed in previous chapters, we estimate the frequency and luminosity of the GWs from the photon sphere of SMBHs. In Section 5.1, assuming the simple accretion geometry discussed in Section 3.4, we derive the typical frequency of the GWs.
In Section 5.3, we derive the luminosity of the GWs from the photon sphere of a single SMBH with the aid of formulae derived in Section 5.2. Finally, in Section 5.4 we estimate the energy density parameter of the stochastic GWs background formed by the SMBHs in the universe.

・Chap.6:　Application to Axion Search

The interaction between photon and graviton has the same form as that of photon and axion. Due to this duality, in the photon sphere of SMBHs, the photon axion conversion also becomes efficient. The conversion causes the dimming of the photon sphere in a certain frequency range by the number of photons that are converted into axions.
In this chapter, we propose the above idea as a new method for searching the axions. As a trial, the dimming rate of the photon sphere of M87* is estimated using the technique developed in Chapter 5.

・Chap.7:　Conclusion

We draw our conclusion.

・Appendices

For a better understanding of the main part, we have included the following appendices:
Appendices A.2 and A.3 provide the hydrodynamic and thermodynamic formulae required to understand Chapter 3.
Appendices A.1 and A.4 provide the formulae used in Chapter 4.
Appendix A.5 is the derivation of the formula used in Chapter 5.
Appendix A.6 is the review of the axion photon conversion discussed in Chapter 6.
Appendix A.7 provides the unit conversion from natural units.

（別紙１）　論文審査の結果の要旨

氏名	齊藤　海秀		
論文題目	High frequency gravitational waves from photon sphere of supermassive black holes 「超巨大ブラックホール光子球からの高周波重力波」		
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	副　査		印

要　　旨

本論文の要旨は以下のとおりである。

本論文の骨子は、第１章で研究の背景、第２章でブラックホール周りの測地線、第３章でブラックホールへのアクリーション、第４章で光子・重力子転換現象、第５章で超巨大ブラックホールの光子球からの高周波重力波、第６章でアクシオンへの応用、第７章でまとめとなっている。

第１章では導入として、重力波研究の現状と超巨大ブラックホールからの高周波重力波を研究することの動機付けが明確に記述されている。

第２章は、ブラックホール時空における測地線のレビューと光子球について本論文で必要となる事項が要領よく説明されている。

第３章では、ブラックホールへのアクリーションに関するモデルの詳細が解説されており有用な内容となっている。特に、光子球にどれだけの光子が存在するかを評価するために重要となるアクリーションディスクからのＸ線放射スペクトルに関する現状がよくまとめられている。

第４章では、光子・重力子転換現象が基礎から説明されている。

第５章が本論文のメインパートであり、超巨大ブラックホールの光子球から、光子・重力子転換現象によって放射される高周波重力波が定量的に評価されている。宇宙における超巨大ブラックホールからの高周波重力波の密度パラメーターへの寄与を世界で初めて定量的評価したことは評価に値する。

第６章では、光子・重力子転換同様に、光子球において光子・アクシオン転換によってアクシオンが放射される可能性を指摘している。これ暗黒物質問題解決にとって重要な知見であり、将来の研究の進展の基礎を与えるものである。

第７章では、まとめと展望が述べられている。

付録には、有用な事項がまとめられている。

2015 年の重力波初観測以来、重力波研究の進展は目覚しく、将来の重力波観測のさらなる進展によって多波長重力波研究の発展が期待されている。特に基礎物理学的観点からは高周波重力波観測の重要性は高い。しかし、存在が確実である重力波源が知られていないため、検出器開発は滞り気味である。そのような状況下で、存在が確実である高周波重力波の新たな重力波源を明らかにした本研究は、今後評価を高めていくと期待できる。

本研究は、高周波重力波の発生源としてブラックホールの光子球からの重力波の可能性を示したものであり、重力波研究の重要な知見を得たものとして価値ある研究の集積であると認める。

よって，学位申請者の齊藤海秀氏は，博士（理学）の学位を得る資格があると認める。

- 特記事項　なし
- 特許登録数　０件
- 発表論文数　　査読付き３編