Ultralight scalar field dark matter in modified gravity theories

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論 文 内 容 の 要 旨

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専　攻　物理学

論文題目（外国語の場合は，その和訳を併記すること。）

Ultralight scalar field dark matter in modified gravity theories

（修正重力理論における超軽量スカラー暗黒物質）

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In this thesis a gravitational phenomenon that is caused by ultralight scalar field dark matter is studied in the framework of modified gravity theories. The most important result obtained in this research is the discovery of a nontrivial resonant oscillation of the gravitational potential induced by the oscillating pressure of ultralight scalar field dark matter.

Currently, dark matter and dark energy are the most serious unsolved problems in physics. As for dark matter, weakly interacting massive particles (WIMPs) have been thought to be the most plausible candidate for dark matter. However, the collider experiments have not reported any signature of WIMPs. This fact motivates people to study other possibilities for dark matter.

The ultralight scalar field dark matter model recently attracts much attention. This is partly because it could resolve the so-called "small scale crisis" of the standard cold dark matter model, which is essentially due to the pressureless nature of cold dark matter. A distinguishable feature of ultralight scalar field dark matter is the oscillating pressure arising from the oscillation of the field. This pressure suppresses the evolution of small scale structures. Thus it is considered to be possible to resolve the "small scale crisis" by ultralight scalar field dark matter.

The oscillating pressure causes another interesting phenomenon. Khmelnitsky and Rubakov pointed out that the oscillating pressure of ultralight scalar field dark matter causes the oscillation of the gravitational potential via Einstein's equation, which could be observed by future experiments. Their study is based on general relativity, which is widely considered to be a fundamental theory of gravity. However, there are some reasons to assume that the theory of gravity should be different from Einstein's theory.

A major reason to consider alternative theory of gravity is the necessity of inflationary phase in early universe and dark energy. The inflationary expansion is thought to be necessary to explain the horizon and flatness problems. Inflation also predicts the primordial fluctuations in matter distribution, which is preferred by the CMB observations. We also know that the present universe is in another accelerating phase, which is caused by dark energy. The simplest way to accelerate the universe is introducing the cosmological constant. However, the cosmological constant suffers from the fine-tuning problems. Then people try to explain these facts by modified gravity theories.

An interesting phenomenon caused by ultralight scalar field dark matter mentioned above is investigated only based on Einstein's theory of gravity. Since we can assume alternative gravity theories, it would be worth reinvestigating this phenomenon in the framework of modified gravity theories. The purpose of this research is to study how the phenomenon caused by ultralight scalar field dark matter changes when considering alternative theories of gravity. In the thesis, we focus mostly on the $f(R)$ theory since it is one of the simplest modified gravity theories.

Remarkably, we have discovered the resonant amplification of the gravitational potential, which is absent in general relativity. This comes from the fact that the $f(R)$ theory includes a new dynamical degree of freedom dubbed the scalaron. The dynamics of the scalaron field is excited by the oscillating pressure of ultralight scalar field dark

matter. If the angular frequency of the pressure, which is twice as the mass of the ultralight scalar field, is sufficiently close to the mass of the scalaron, the scalaron field is amplified dramatically. Since the gravitational potential is determined by the scalaron field in the $f(R)$ theory, the gravitational potential is also amplified in that situation. We have also found that the resonance behavior also appears when the fraction of the angular frequency of the pressure and the scalaron mass is close to an arbitrary rational number. If the resonant oscillation is excited, the oscillation of the gravitational potential is expected to be detected by future gravitational experiments.

This thesis is organized as follows:

- Chap. 1 is for the introduction to the research. The dark matter and dark energy problems are explained, and the purpose of the research is described.

- In Chap. 2, the ultralight scalar field dark matter model is reviewed. In Sec. 2.1 motivations for ultralight scalar field dark matter and its possible origins in particle theory are explained. We see some properties of ultralight scalar field dark matter in Sec. 2.2, where we especially focus on differences from the standard cold dark matter model. We first discuss the homogeneous expansion of the universe and show that ultralight scalar field dark matter can explain the history of the universe correctly. Then we investigate the linear perturbations, and introduce an important scale called the "Jeans scale" that characterizes the behavior of ultralight scalar field dark matter. Finally, we discuss the distribution of dark matter in the galaxy. In Sec. 2.3, the existing constraints on ultralight scalar field dark matter are summarized. We see that the ultralight scalar field dark matter model is consistent with all the observed data if the mass satisfies $m \gtrsim 10^{-22}$ eV. In Sec. 2.4 we discuss a phenomenon that the oscillation of the gravitational potential is induced by the oscillating pressure of the ultralight scalar field dark matter. This phenomenon is pointed out by Khmelnitsky and Rubakov, which is reinvestigated in the framework of modified gravity theories in Chap. 4 and Chap. 5. In this section, we also introduce two direct detection methods for this oscillating gravitational potential. One is utilize pulsar timing array experiments proposed by Khmelnitsky and Rubakov, and the other is utilize gravitational wave laser interferometers proposed by us.

- In Chap. 3, modified gravity theories are reviewed. In Sec. 3.1 motivations for alternative theories of gravity are explained. In Sec.3.2, we introduce the $f(R)$ theory, which is the simplest example of modified gravity theory. We discuss the relation of the $f(R)$ theory to the scalar-tensor theory and other modified gravity theories. In Sec. 3.3 constraints on the $f(R)$ models are summarized.

- Chap. 4 and Chap. 5 are the main parts of the thesis. We reinvestigate the phenomenon that the gravitational potential is induced by the oscillating pressure of ultralight scalar field dark matter in the framework of $f(R)$ theory.

  Chap. 4 is for deriving the formula for calculating the oscillating part of the gravitational potential. In Sec 4.1, we derive the formula in the original $f(R)$ theory.

  In Sec 4.2, we move onto the scalar-tensor formalism of the $f(R)$ theory, where we can see the phenomenon more clealy. In the scalar-tensor formalism, we can understand the system by analyzing the dynamics of the scalaron field, which is the new degree of freedom in the $f(R)$ theory. The scalar-tensor formalism is also useful for numerical calculations.

  In Chap. 5, we study specific $f(R)$ models in order. In Sec. 5.1, we study the quadratic model, where the function $f(R)$ is quadratic in R, i.e., $f(R) = R^2/6M^2$. This model can be solved analytically, and is useful to understand the underlying physics, while the model cannot satisfies the constraints from the observations. By analyzing this model, we can see a resonant oscillation of the gravitational potential, which is absent in general relativity. The condition for resonance turns to be that the angular frequency of the pressure and the mass of the scalaron are sufficiently close to each other. In Sec. 5.2, we study the exponential model $f(R) \sim \exp(-R)$. This model is a bit more realistic in the sense that it can pass the local gravity constraints. The model, however, cannot utilize for explaining dark energy without a modification. In analyzing the exponential model, we encounters the nonlinearity of the equation of motion for the scalaron, and see nonlinear feature of resonant oscillation. Remarkably, in the nonlinear oscillation, there appear new resonances at the points that the ratio of the angular frequency of the pressure and the scalaron mass is an arbitrary rational number. In Sec. 5.3, we study the cosmological dark energy models known as the Hu-Sawicki and Starobinsky model. These models can explain dark energy, and at the same time can pass the local gravity constraints.

- Chap. 6 is devoted to the conclusion.

（別紙１）　　　　　　　　　　　論文審査の結果の要旨

氏名	青木　新
論文題目	Ultralight scalar field dark matter in modified gravity theories （修正重力理論における超軽量スカラー暗黒物質）

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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章で超軽量スカラー場がなぜ暗黒物質の候補となり得るのか、第３章で修正重力理論のレヴュー、第４章で超軽量スカラー場を修正重力理論の枠組みで考察、第５章ではオリジナルな解析、第６章で結論、となっている。

第１章では導入として、宇宙論の大問題である暗黒物質研究の現状と本研究の動機が明確に記述されている。

第２章では、まず、超軽量スカラー場を考える動機が説明され、素粒子論との関連が述べられている。次に、超軽量スカラー場のダイナミクスと揺らぎの理論が解説されている。また、超軽量スカラー場への宇宙背景放射観測とライマンアルファ吸収線観測からの制限がまとめられている。さらに、超軽量スカラー場の直接観測方法が説明されている。特に、最後の干渉計によるスカラー場観測の方法はオリジナルな業績であり、重要な成果である。

暗黒物質とともに暗黒エネルギーは物理学における重要な未解決問題である。これまで暗黒エネルギーに関して様々な研究がなされてきたが、暗黒エネルギーを修正重力理論で説明する試みは有力な可能性であるとみなされている。この立場に立つならば、修正重力理論の枠組みで暗黒物質問題を考えなければならない。そこで、第３章では、修正重力理論の理論的な基礎と重力理論の修正に対する観測からの制限が非常によくまとめられている。

第４章では、修正重力理論の典型である高階重力理論の枠組みにおける超軽量スカラー場の理論的な定式化が展開されている。特にスカラーテンソル重力理論との関係が簡潔にまとめられている。

第５章では、超軽量スカラー場暗黒物質の具体的なモデルが研究されている。本論文の最も重要な成果は、高階重力理論においてスカラロンと呼ばれるスカラー場と暗黒物質の候補である超軽量スカラー場との共鳴現象に着目した点であり、そのことによりスカラー場暗黒物質の観測可能性が高くなることを示した点は評価に値する。高階重力理論に限らず、ほとんどの修正重力理論にはスカラロンのような余分なスカラー場が含まれており、本論文で指摘された共鳴現象は普遍的な現象であると考えられ、その意味において本論文の成果は高い価値を有するものである。

第６章で結論が述べられている。

本研究は暗黒物質としてのスカラー場を修正重力理論の枠組みにおいて研究したものであり，暗黒物質の有力な候補である超軽量スカラー場の観測可能性について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，学位申請者の青木新氏は，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
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