論文の内容の要旨

Evolution of Low- and Intermediate-mass Stars with Physics beyond the Standard Model

（小・中質量星の進化を用いた標準模型を超えた物理の探索）

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The Standard Model (SM) of particle physics provides the fundamental framework of elementary particles and interactions between them. Although it explains most results of terrestrial experiments, the SM is still on the way to the Theory of Everything. In order to search for a hint of physics beyond the SM, stars have been used as a probe of new physics which complements terrestrial experiments. In this thesis, I study the effects of the neutrino magnetic moment (NMM) and the large extra dimensions (LEDs) on low- and intermediate-mass stars.

Observations of neutrino oscillation have revealed that neutrinos are massive, although their mass is still unknown. Particle theories predict that such massive neutrinos have a magnetic moment. The SM with Dirac neutrinos predicts NMM of $\sim 10^{-19} \mu_B$, where μ_B is the Bohr magneton. This value is so small that terrestrial experiments and astrophysical observations cannot find its signature in near future. However, some theories beyond the SM predict that NMM can be as high as $\sim 10^{-12} \mu_B$. Since its value is model-dependent, measurement of NMM is a key to physics beyond the SM. NMM has been explored by neutrino-electron scattering experiments, but it is desirable to search for astrophysical signatures of NMM to obtain tighter limit.

Gravity is another open problem in particle physics. Since it is difficult to quantize it, gravity is not included in the SM. Also, the reason why gravity is much weaker than the other interactions is not known. In order to solve this hierarchy problem, the idea of LEDs has been discussed. If n extra dimensions are compactified, the gravitational scale in the $(n+4)$-spacetime can be as low as the electroweak scale. LEDs have been explored by torsion balance experiments because they modify the inverse-square law. Also, Kaluza-Klein (KK) gravitons excited by LEDs have been searched by high-energy collider experiments. KK gravitons emitted from hot plasma potentially affect stellar evolution.

In Chapter 2, I study the effects of NMM and LEDs on intermediate-mass stars which form a blue loop on the Hertzsprung-Russell diagram during central helium burning. Since morphology of the blue loop is sensitive to input physics, it is expected that new physics also affects the evolution of intermediate-mass stars. If neutrinos have a finite magnetic moment, an extra energy loss is induced by neutrino emission. Similarly, LEDs induce an energy loss from stellar plasma because of KK graviton emission. I implement additional energy losses induced by NMM and LEDs in a stellar evolution code and calculate the evolution of intermediate-mass stars. I find that the NMM leads to elimination of the blue loops during core helium burning. Some of stars in the blue loop are observed as a Cepheid variable when they cross the instability strip. In order for Cepheids to exist, the NMM should be smaller than the range ~2×10^{-10} to $4\times10^{-11}\,\mu_B$ depending on the $^{12}C(\alpha,\gamma)^{16}O$ reaction rates.

LEDs are also explored in my study. Since the n=1 model is clearly excluded by the square-inverse law on a large scale, I focused on the n=2 case which is the simplest possible model. It is found that the fundamental scale in the (4+2)-spacetime should be larger than ~2 to 5 TeV in order for the blue loop not to be eliminated. The constraints given by intermediate-mass stars are found to be weaker than the current experimental and astrophysical limits, but they offer an independent method to explore new physics.

In Chapter 3, I study the effect of NMM on the lithium abundance in low-mass stars. This part is motivated by a recent study that discovered ubiquitous lithium production in advanced evolutionary stages of low-mass stars. Since lithium is easily destroyed when it is conveyed to the inner hot region, the high surface lithium abundance has not been predicted by stellar theories. In order to mitigate this problem, I applied the effect of the NMM on the low-mass stellar evolution. Because of the additional energy loss, a more massive and smaller helium core is formed at the tip of the red giant branch. The smaller core leads to a less dense envelope. As a result, thermohaline mixing at the bottom of the envelope becomes more active and ^7Be produced in the hydrogen burning shell is conveyed to the convective envelope. The lithium abundance in red clump stars hence becomes larger when the NMM is considered. I conclude that the lithium problem is mitigated when the NMM of ~$(2-5)\times10^{-12}\,\mu_B$ is adopted. Although this value is higher than the tightest upper limit that comes from stellar evolution, the constraint is not robust because it can depend on numerical codes for stellar evolution which are used to compare stellar models with observed stars. Also, additional energy losses can be induced by other physics including coupling between axion-like particles and electrons. This result opens up a new possibility of mitigating the lithium problem with additional energy losses induced by physics beyond the SM.