Constraining the secular variation of the gravitational constant using white-dwarf stars spectra

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Research Article

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Constraining the secular variation of the gravitational constant using white-dwarf stars spectra

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Abstract.

Context. Astrophysical observations play a critical role in the possibility of variations in fundamental physical constants. One of the ways of probing these variations would be based on the evolution of the white-dwarf stars.

Aims. We use the spectrum of white-dwarf star G191-B2B to find an upper limit on the possible deviation of the gravitational constant with strong gravitational fields.

Methods. We analyze archive observation of the Hubble Space Telescope Imaging Spectrograph (HSTIS) to determine the possible cosmological deviation of the gravitational constant from the observed gravitational redshift.

Results. Our analysis provided a strong estimate on an upper bound on the possible space-time variation of the gravitational constant $\dot{G}/G = (0.238 \pm 2.959) \times 10^{-15}\,\mathrm{yr}^{-1}$ *comparing with previous results.*

Conclusions. The obtained result in this study offers the possibility of testing parameters of modern unification theories.

Keywords*:* varying fundamental physical constants; varying gravitational constant; white-dwarf stars spectra; absorption spectra analysis; GUTS

1. Introduction

General Relativity is currently known as the General Theory of Relativity. It is due to the equivalence principle, which assumes that the gravitational constant does not vary with space-time. Based on the general assumption, the constancy of G is an empirical question that would be studied through astrophysical observations and experimental methods. In particular, several modern theories of grand unification, the gravitational constant is varying slowly as a function of low-mass dynamical scalar fields [1–3]. As a result, the theoretical approaches describe that the fundamental constants such as the fine-structure constant, $\alpha = e^2/\hbar c$, the proton-to-electron mass ratio, $\mu = m_p/m_e$, and the gravitational constant, G would vary over cosmological timescales. In recent years, numerous studies constrained on space-time variations in both α and μ with a wide range of redshifts ($0.5 < z < 3.5$). These results indicated that both α and μ are consistent with a space-time varying based on astrophysical observations and experimental methods [4-8]. The most important results were introduced by the Many-Multiplet (MM) method, which used the spectral lines from astrophysical observations to search for the fine-structure constant variation in the temporal and spatial dimensions. However, the MM method required accurate laboratory wavelengths very highly with uncertainties of $1{:}10^{7}$ or better to be employed productively, since the improvements of α were at a level of 10^{-6} and μ were at a level of 10^{-7} [9-12]. Recently, the variation of both α and μ could be improved by using the ammonia and methanol from most of the observations [13]. At the same time, the other works focused on a study of G-varying with cosmological timescales [14]. Almost studies indicated that the values of the fundamental physical constants were different rates at different locations and regions in the Universe [15]. Accordingly, it is interesting that many methods proposed to assume the G-variation with cosmological timescales. The most stringent limit on this variation was found by using Big Bang nucleosynthetic $-0.3 \times 10^{-12}\ \mathrm{yr}^{-1} \leq \dot{G}/G \leq 0.4 \times 10^{-12}\ \mathrm{yr}^{-1}$ [15, 16] while the analysis of the Lunar Laser Ranging experiments gave a better limit $\dot{G}/G = (0.2 \pm 0.7) \times 10^{-12}\ \mathrm{yr}^{-1}$ [17]. It should be noted that Big Bang nucleosynthetic arguments are model-dependent, whereas Lunar Laser Ranging presents only local limits to the secular rate of G-varying. Other studies used the Hubble diagram of Type Ia supernovae to provide a weaker limit $\dot{G}/G \sim 1 \times 10^{-11}\ \mathrm{yr}^{-1}$ at $z \sim 0.5$ [18, 19]. Recently, the limits of G-varying have improved with high accuracy as $-(1.10 \pm 1.07) \times 10^{-12}\ \mathrm{yr}^{-1} < \dot{G}/G < 0$. The best constraints bound $-0.6 \times 10^{-12}\ \mathrm{yr}^{-1} \leq \dot{G}/G < 0$ [20-26]. The linked space-time variation between α and G would be related by $\dot{\alpha}/\alpha^{2} \sim \dot{G}/G$ based on the model-dependent. Current studies used high-resolution of astrophysical observations to improve the most stringent limits on this variation, for example, $\Delta\alpha/\alpha = (0.007 \pm 0.087) \times 10^{-6}$ for the fine-structure constant and $\Delta\mu/\mu = (0.025 \pm 0.262) \times 10^{-7}$ for the proton-to-electron mass ratio [29-31].

In this study, we used white-dwarf star spectra to set a new limit to the secular rate of G. In this case, we combined to examine the [Fe V] from the white-dwarf star G191-B2B and their corresponding in the laboratory. The spectra observed from the Hubble Space Telescope Imaging Spectrograph. It has a mass of $M = 0.51 M_{\odot}$ with a radius of $R = 0.022 R_{\odot}$, and gravitational redshift $z = \Delta\phi \approx 5 \times 10^{-5}$ with the average total redshift of [Fe V], $z_{abs} = 7.78 \times 10^{-5}$ [32, 33], that is the best candidate to search for G-variation over cosmological timescales. The expected result derived an effect of time-varying in G providing an upper bound in comparison with previous results [9-14, 34]

2. Bounds on $\dot{G}/G$.

Astrophysical observations provide a natural way to look for a variation of the fundamental physical constants, such as the fine-structure constant, the proton-to-electron mass ratio, the gravitational constant and the other constants. White dwarf stars provide us an independent way of searching for any possible variation of the gravitational constant, G. Because white-dwarf stars are known as extremely long-lived stars in the Universe. Therefore, the timescales of the evolution of the white-dwarf stars allow us to test the effect of time-varying in G event for the changed-rates of G was very slow. On the other hand, the end-point of stellar evolution for almost stars is white-dwarfs that have long enough times and very sensitive to the accurate value of the gravitational constant. The evolution of white-dwarf stars is well-understood and it can be well described such as a simple gravothermal process with large luminosities and low temperatures [35]. Recent studies indicated that the specific rate of white-dwarf stars cool is not only sensitive to the changed-value of G but also to the effect time-varying in G since they were born [36, 37]. It is interesting to note that astrophysical observations provide us an important tool to test, whereas the fundamental constants vary with cosmic space and timescales during the evolution of the Universe. White-dwarf stars spectra are well known as the best candidate choice for this purpose. The variations of the fine-structure constant, the proton-to-electron mass ratio and the gravitational constant would be determined with high accuracy based on these observations and measurements. In particular, we can easily describe models to phenomena way, which allow for the identification of the space-time variations of the fundamental constants. Therefore, their spectra could be the best candidate choice for this purpose. Based on the model-dependent, the assumption one can obtain the relationship between α and G as follows [38].

$$\frac{\Delta G}{G} = [1.6R + 0.4(1 + S)]\frac{\Delta\alpha}{\alpha}$$

Where both dimensionless parameters S and R related to Electroweak and Quantum Chromodynamics. Their values are different based on the used models of differences. These values can be determined by astrophysical data and they could be applied to search for the effect of the fundamental constants-varying. At the phenomenological level, the choice $R = 273 \pm 86$ and $S = 630 \pm 230$ [31, 34, 38]. It should be noted that the variations of α and G based on the parameters R and S. There was also a significant dependence on the choice of priors. In particular, the broad case will lead to preferred values of α and G that are smaller since a broader prior increase the fraction of the volume of parameter space with large values of R or S. Therefore, our study aims to constrain consist with the assumption of a uniform prior in the R and S parameter space. In this way, our result should bring best-fit values to a significant result. However, a difficult problem that should be noted about the detailed knowledge of the physics of unification as it should be difficult to identify a physically motivated choice of prior for both R and S. Based on our previous fitting program, the fit value of the parameters (R, S, α) was also compatible with other works [33-38]. By using our fitting program one can obtain approximately the fitted-value of quantity G. The presented study here aims to use the combined wavelengths of [Fe V] from the white-dwarf star G191-B2B spectra and their laboratory values to constrain the effect of time-varying in G over cosmological timescales. The spectrum of white-dwarf star G191-B2B included several interesting absorptions. This white-dwarf star is usually sensitive to $\Delta\alpha/\alpha$ due to the [Fe V] and [Ni V] transitions, as we have indicated in the previous works [29-38]. From comparisons of different [Fe V] lines, one can obtain measurements of several fundamental constants such as the fine-structure constant, the proton-to-electron mass ratio and the gravitational constant. Our study used the same procedure of analysis with non-linear least-squares methods [29-38]. Using simultaneously of χ^2-minimizing with all free parameters including column density N, the absorption redshift z_{abs}, the Doppler, and line width b, we estimated $\dot{G}/G$ and it associated with the error in each observed line of [Fe V]. We combined the values of $\dot{G}/G$ from different absorbers of [Fe V]. To do for the excess dispersion in the used data above, $\sigma_{tot}^2 = \sigma_{\dot{G}/G}^2 + \sigma_{sys}^2$ determined the statistical error until $\Delta\chi^2 = 1$. The methods and methodology would be described in detail in the previous works [9-14, 33-38]. The results of this analysis are illustrated for $\dot{G}/G$ in **Figure. 1** with the expected result $\dot{G}/G = (0.238 \pm 2.959) \times 10^{-15}\,\mathrm{yr}^{-1}$. The results of this analysis are illustrated for $\dot{G}/G$ in **Figure. 1** with the expected result $\dot{G}/G = (0.238 \pm 2.959) \times 10^{-15}\,\mathrm{yr}^{-1}$.

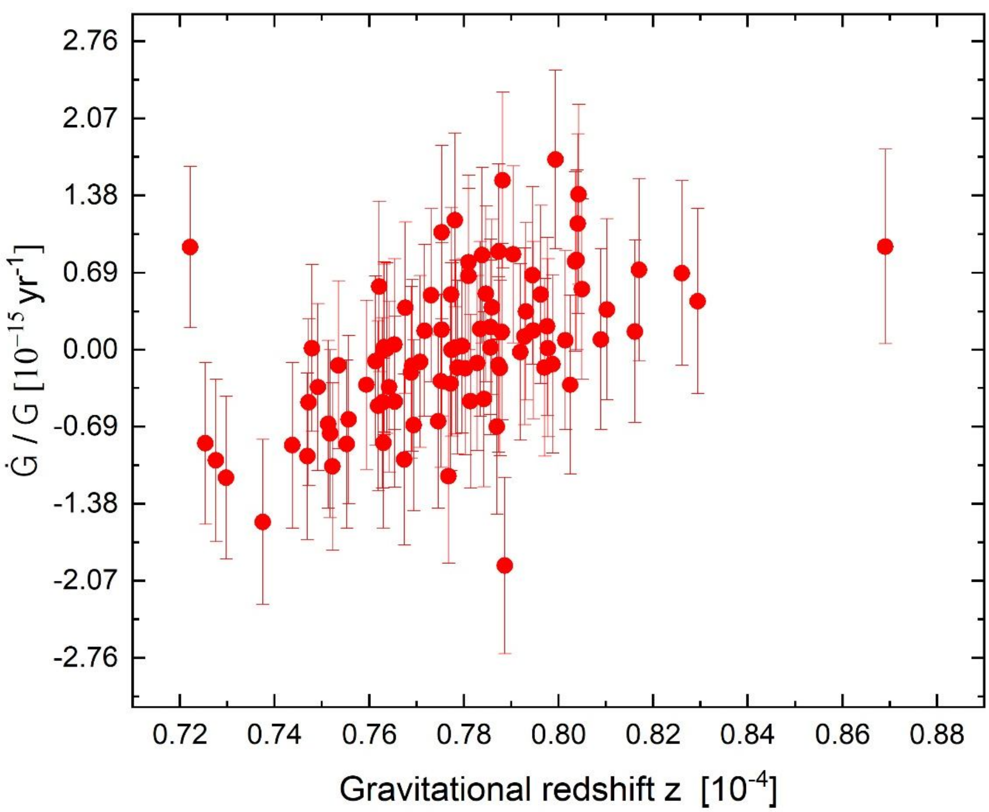

Figure 1. Illustration for $\dot{G}/G$ versus gravitational redshift.

3. Discussion and Conclusions.

The current framework of particle physics indicates that the Standard Model is not complete because it can only explain 4% of the energy density contented in the Universe. As a result, astrophysical observations would provide a key tool for theoretical extensions in both the Standard Model and cosmology to detect the variation of the fundamental physical constants. Therefore, theories propose to unify gravitation with other fundamental forces by including additional spatial dimensions correspond to varying-constants over cosmological directly. In this context, the possibility of varying fundamental constants would be studied through the redshifted spectra of observational systems. These systems were used as a means to probe in the case of the varying of fine-structure constant, the proton-to-electron mass ratio and the gravitational constant. The indicated fundamental constants-varying with cosmological timescales would demonstrate new physics beyond the Standard Model of particle physics. In this way, we would confirm the existence of phenomena based on the cosmological frame. That would allow us to prove the incompleteness of the Einstein Equivalence Principle. In particular, studies on G-varying over cosmological timescales plays an important role in Grand Unification Theories. As a result, observed data of pulsating white-dwarfs of G117-B15A and R548 showed the effect of timing variation of G as follows $\dot{G}/G \sim -1.8 \times 10^{-10}\,\mathrm{yr}^{-1}$ and $\dot{G}/G \sim -1.3 \times 10^{-10}\,\mathrm{yr}^{-1}$. The other studies used white-dwarf asteroseismology obtained $\dot{G}/G = 1.3 \times 10^{-10}\,\mathrm{yr}^{-1}$ [39-41]. Making use of the white cooling theory, the effect variation of G could be improved better $\dot{G}/G \leq 10^{-10} - 10^{-11}\,\mathrm{yr}^{-1}$ [42] and $\dot{G}/G \sim -1.8 \times 10^{-12}\,\mathrm{yr}^{-1}$ from applying the Galatic cluster NGC6791 [43]. Upper limits to the rate of change of G based on the pulsar binary of PSR1913+16 and Brans-Dicke theory were $\dot{G}/G = (1.0 \pm 2.3) \times 10^{-11}\,\mathrm{yr}^{-1}$ and $\dot{G}/G = (1.0 \pm 2.3) \times 10^{-11}\,\mathrm{yr}^{-1}$. On the other hand, other studies reexamined this data and combined with the PSR B1855+09 to determine $\dot{G}/G = (4 \pm 5) \times 10^{-12}\,\mathrm{yr}^{-1}$ and $\dot{G}/G = (-9 \pm 18) \times 10^{-12}\,\mathrm{yr}^{-1}$ [44-46]. Recently derived a set of upper bound constraints $|\dot{G}/G| < 1.6 \times 10^{-12}\,\mathrm{yr}^{-1}$ referring the comparison data of six telescopes while the most stringent constrained $\dot{G}/G = (-0.6 \pm 4.2) \times 10^{-12}\,\mathrm{yr}^{-1}$ at 2σ using p-mode spectra [47-55]. However, all the current studies would only estimate the G-varying at a level of $10^{-12}\,\mathrm{yr}^{-1}$.

In this study, we studied the effect of time-varying in G over the evolutionary properties of white-dwarf stars. The most stringent limit on this effect was found $\dot{G}/G = (0.238 \pm 2.959) \times 10^{-15}\,\mathrm{yr}^{-1}$ using the combined wavelengths of [Fe V] from the white-dwarf star spectra G191-B2B and their laboratory values. This result demonstrates significant internal consistencies with G-varying slowly over cosmological timescales. This study provides an upper bound limit on $\dot{G}/G$ better than previous works using Pulsar timing, Lunar Laser Ranging, Big Bang nucleosynthesis and Ages of globular clusters. Moreover, the assumption is as the effect of time-varying in G should be estimated more accuracy using various models with extra dimensions as $\dot{G}/G \sim +10^{-15}\,\mathrm{yr}^{-1}$ [56] consistent with our result. In the future, with the best selection candidate such as CH_3OH, OH and CH molecules will have significantly increased the sensitivities of this effect.

Motivated by the possibilities of space-time variations of the fundamental constants should play an essential role in checking for the parameters of the Grant Unification Theories [57].

Declaration of Competing Interest

The author declares no conflict of interest.

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