Limits on the variability of the Fine-Structure Constant over cosmological space-time

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Limits on the variability of the Fine-Structure Constant over cosmological space-time

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Abstract. The fine-structure constant plays an important role in the measurement of the strength of the electromagnetic interaction and it quantifies the strength with electrons bound within atoms and molecules. A new method provides complementary constraints on its value with the most precise estimations made so far.

1. Introduction
Many modern theories predict that the values of fundamental constants vary over space and time such as the fine-structure constant, \( \alpha = \frac{e^2}{4\pi e_0 hc} \), which is motivated by theories unifying the fundamental interactions [1]. The search for variations of these constants can be detected by comparing transitions between levels in atoms and molecules from astronomical observed data that have a different functional dependence on these constants. Up to very recently, tests of \( \alpha \)-variation over cosmological time scales were based on the comparisons of atomic clocks and observations of high redshift objects with their corresponding laboratory values at \( z = 0 \) [2-5]. The most sensitive current limits on \( \alpha \) comes from measurements using microwave and mm-molecular transitions such as hydrogen give null results for \( \Delta \alpha / \alpha \) at the level of a few parts per million (ppm) [6-8]. Here, we propose to use the absorption lines identified as Fe V and Ni V transitions toward the white dwarf G191-B2B [9] with the aim of constraining past spatial and temporal variations in \( \alpha \). The current analysis is based on absorption lines, the constraints on \( \Delta \alpha / \alpha \) are stronger than those derived by other methods.

2. Data analysis
To extract whether \( \alpha \) changed over the cosmological time and space scales, we have applied the method first suggested by Le [10] to the fine splitting of the transition lines of Fe V, Ni V, observed in the spectra of white dwarf G191-B2B with high resolution far-UV spectrum. According to this method, the relationship between the laboratory wavelengths and those observed near the white dwarf is approximately written as

\[
\frac{\Delta \alpha}{\alpha} \approx \frac{1}{2} \left( \frac{2\lambda_{1}(0)}{2\lambda_{1}(1)} \right)^{-1} \left( \frac{2\lambda_{2}(0)}{2\lambda_{2}(1)} \right)^{-1} - 1, \]

provided that \( \Delta \alpha / \alpha \) is very small. Thus, any variation of \( \alpha \) could be revealed by comparing different transitions in different atoms in cosmic and laboratory, one can directly infer the possible variation of \( \alpha \) at different epochs, space-time points, regions of the Universe and the present value. With those measurements and existing of Fe V and Ni V in the white dwarf star G191-B2B recorded by the Hubble Space Telescope Imaging Spectrograph,
we constrain variation of \( \alpha \) and open a new way for future radio astronomy measurement of higher accuracy to test more stringently whether the \( \alpha \) varies. This uncertainty can be used to estimate systematic error in the determination of \( \Delta \alpha / \alpha \). The discussions of possible sources of systematic and statistical errors of the method are as described in [9-10]. Combining these results with other stringent limits on \( \Delta \alpha / \alpha \) obtained from comparisons of transition wavelengths in some molecules such as H\(_2\), NH\(_3\), CH and CD constrain \( \Delta \mu / \mu \) in the future [11-13]. Fig. 1 and 2 show the limit obtained from the analysis the Fe V and Ni V absorption lines from the white dwarf star G191-B2B spectra to constrain past variations in \( \alpha \).

![Figure 1. Plot for the components of Fe V.](image1)

![Figure 2. Plot for the components of Ni V.](image2)

3. Conclusions

The most stringent limit derived here is statically more constraining than that derived in the past test by the methods used in previous studies [13, 15, 18-20]. This remarkably consistent indication for a possible variation of \( \alpha \) certainly deserves further investigation on a large number of systems, aimed at reducing the final error bar. It suggests how dedicated astronomical measurements can improve these constrain in the future with very high resolution spectroscopic studies are needed to probe the variations in \( \alpha \) with much better accuracy. With improvement from astronomical measurements and in laboratory wavelengths, the study of the variation of the fundamental constants such as the fine structure constant should also be of utmost for a complete understanding of fundamental physics.

References