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Conference Report

Probing the Gravitational Dependence of the Fine-Structure Constant from Observations of White Dwarf Stars

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Abstract: Hot white dwarf stars are the ideal probe for a relationship between the fine-structure constant and strong gravitational fields, providing us with an opportunity for a direct observational test. We study a sample of hot white dwarf stars, combining far-UV spectroscopic observations, atomic physics, atmospheric modelling, and fundamental physics in the search for variation in the fine structure constant. This variation manifests as shifts in the observed wavelengths of absorption lines, such as quadruply ionized iron (FeV) and quadruply ionized nickel (NiV), when compared to laboratory wavelengths. Berengut et al. (*Phys. Rev. Lett.* **2013**, *111*, 010801) demonstrated the validity of such an analysis using high-resolution Space Telescope Imaging Spectrograph (STIS) spectra of G191-B2B. We have made three important improvements by: (a) using three new independent sets of laboratory wavelengths; (b) analysing a sample of objects; and (c) improving the methodology by incorporating robust techniques from previous studies towards quasars (the Many Multiplet method). A successful detection would be the first direct measurement of a gravitational field effect on a bare constant of nature. Here we describe our approach and present preliminary results from nine objects using both FeV and NiV.

Keywords: varying constants; varying alpha; hot white dwarf stars; absorption spectra analysis

A common feature of many schemes to unify the strong, electro-weak, and gravitational forces of nature is the prediction of violation of local Lorentz invariance and the Einstein equivalence principle at high energy [1]. This can manifest itself as variations in the fundamental constants of physics (Newton's constant, G; proton-to-electron mass ratio, μ; fine structure constant, α; etc.) due to light scalar fields, the presence of extra space dimensions, or the non-uniqueness of the quantum vacuum state for the universe. Probing the variation of fundamental constants in the distant universe is an important test of the equivalence principle and prospective theories of Grand Unification.

In a light scalar field the total mass and the total scalar charge are both proportional to the number of nucleons, for objects that are not too relativistic, so observing fundamental constants near gravitating massive bodies is one way to probe the form of a potential variation and the existence of scalar fields. However, the effect of a light scalar field on fundamental constants near massive bodies depends heavily on the theory being considered, particularly the type of coupling between the scalar fields and other fields [2]. Flambaum and Shuryak (2008) [3] considered a linear coupling between alpha and gravitational potential through the introduction of a massless scalar field, leading to the simple relationship

$$\Delta\alpha/\alpha \equiv \frac{\alpha(r)-\alpha_0}{\alpha_0} \equiv k_\alpha \Delta\phi = k_\alpha \Delta\left(\frac{GM}{rc^2}\right)$$

where ϕ is the dimensionless gravitational potential ($\phi = \frac{GM}{rc^2}$), k_α is a dimensionless dependency parameter, M is the mass of the object, r is the radial distance from the object's center, and α_0 is the laboratory value of the fine structure constant. If the relationship is indeed linear (or close to), then k_α is a constant and can be very accurately determined by high-precision atomic clocks [3–11]. However, k_α may not be constant [12], and the assumption that this relationship is linear needs testing. To probe a non-linear relationship, we need to observe k_α under conditions different than those on Earth.

Hot white dwarf stars are the ideal probe for a relationship between α and strong gravitational fields. Hot white dwarfs—with masses comparable to the sun and radii comparable to Earth—generate strong gravitational fields and are typically bright (enough for precision spectroscopic analysis) with numerous absorption lines. Within the absorption spectra of white dwarfs, variation in α is manifested as shifts in the observed wavelengths of absorption lines when compared to laboratory wavelengths [13], providing us with an opportunity for a direct observational test.

Berengut et al. (2013) [14] recently used Hubble Space Telescope (HST)/Space Telescope Imaging Spectrograph (STIS) spectra of the hot white dwarf star G191-B2B to constrain $\Delta\alpha/\alpha$, by observing the wavelength shifts in 96 quadruply ionized iron (FeV) and 32 quadruply ionized nickel (NiV) absorption features and deriving a separate limit for each metal: $\Delta\alpha/\alpha = (4.8 \pm 1.6) \times 10^{-5}$ for FeV and $\Delta\alpha/\alpha = (-6.1 \pm 5.8) \times 10^{-5}$ for NiV. Berengut et al. (2013) [14] suggest that this inconsistency is due to a systematic effect in the laboratory wavelengths used. We have extended this work by: (a) using new laboratory wavelengths; (b) analysing a sample of objects rather than a single object; and (c) refining the analysis methodology by incorporating robust techniques from previous studies towards quasars (the Many Multiplet method [15–17]).

We are using three new independent lists of laboratory wavelengths to investigate the suspected systematic gain calibration error suspected by Berengut et al. (2013) [14]. This apparent systematic effect is an important problem, because the effect is dependent on transition wavelength—just like a wavelength shift due to $\Delta\alpha/\alpha$. In 2013, there were two lists of laboratory wavelengths available for FeV and NiV with reasonable precision and within the wavelength range of interest: Ekberg (1975) [18] for FeV and Raassen & van Kleff [19] for NiV. Since then, three new lists have become available: the (a) Kramida; (b) Tchang-Brillet; and (c) Nave wavelength lists. Kramida (2014) [20] published an updated list of laboratory wavelengths for FeV, based on more recent observations by Azarov et al. (2001) [21] (outside of our wavelength range of interest) in addition to the Ekberg (1975) [18] laboratory results. Between 2014–2015 Tchang-Brillet (LERMA, Meudon, France) and a group led by Gillian Nave (NIST, Gaithersburg, MD, USA) independently re-observed the FeV laboratory wavelengths [22–24]. The team at NIST also re-observed the NiV laboratory wavelengths. The apparent systematic effect in the Raassen NiV laboratory wavelengths noted by Berengut et al. (2013) [14] does not appear to be present in the new Nave NiV wavelengths from NIST.

In order to study a broader compactness range and to enlarge the size of our sample, we conducted a search of both the literature and the Mikulski Archive for Space Telescopes (MAST). We used the following selection criteria: (a) photospheric absorption lines of FeV or NiV (atomic transitions for which we have new accurate laboratory wavelengths); (b) observed in the far-UV (the wavelength range of the FeV and NiV absorption lines) using HST/STIS Echelle spectroscopy; and (c) signal-to-noise ratio greater than 30 (a threshold for reasonable statistical uncertainties we determined using numerical simulations). We found that only the HST/STIS Echelle spectra provide the necessary wavelength accuracy (1 km$\cdot$s^{-1} [25]) needed for this project. In addition to G191-B2B (the object studied in [14]), we identified nine hot, bright white dwarfs and sub-dwarfs. We were also awarded 12 orbits with HST/STIS (scheduled for autumn 2017) to obtain new far-UV observations of three bright white dwarfs known to have photospheric Fe and Ni absorption lines. Table 1 provides an overview of the 13 objects that will be studied in the course of this project. Our sample includes objects with gravitational potentials spanning four orders of magnitude.

Table 1. Characteristics of the white dwarf and sub dwarf sample. Uncertainties are 1σ. $g = GM/r^2$, the surface gravity in cm$\cdot$s^{-2}.

Object	Type	RA (J2000) (Degrees)	Dec. (J2000) (Degrees)	T_{eff} (K)	log g	Ref.
vz 1128	O(H)	205.569792	28.433639	$36,600 \pm 400$	3.9 ± 0.1	[26]
ROB 162	O(H)	265.159792	−53.642111	$51,000 \pm 2000$	4.5 ± 0.2	[27]
BD + 28°4211	sdO	327.795813	28.863847	$82,000 \pm 5000$	6.20 ± 0.15	[28]
Sh 2-174	O(H)	356.260417	80.950000	$64,000 \pm 2900$	6.94 ± 0.16	[29]
Sh2-313	DAO	193.386496	−22.872984	$80,000 \pm 10,000$	7.2 ± 0.3	[30]
HS0505 + 0112	DAO	77.128458	1.277611	$63,200 \pm 2100$	7.30 ± 0.15	[29]
Ton21	DA	145.711333	26.016647	$69,710 \pm 530$	7.47 ± 0.05	[31]
Feige 24	DA	38.781522	3.732415	$60,000 \pm 1100$	7.50 ± 0.06	[31]
G191-B2B	DA	76.377645	52.831215	$52,500 \pm 900$	7.53 ± 0.09	[31]
REJ0558-373	DA	89.560542	−37.573561	$59,500 \pm 2200$	7.70 ± 0.14	[32]
RE-J0623-371 *	DA	95.800417	−37.691389	$58,200 \pm 1800$	7.14 ± 0.11	[32]
REJ2214-492 *	DA	333.549642	−49.324239	$61,600 \pm 2300$	7.29 ± 0.11	[32]
REJ0457-281 *	DA	74.307917	−28.131667	$51,000 \pm 1100$	7.93 ± 0.08	[32]

* To be observed with Hubble Space Telescope (HST)/Space Telescope Imaging Spectrograph (STIS) during cycle 24.

We examine the spectral data of each object before fitting the absorption lines to identify the FeV and NiV transitions relevant for estimation of $\Delta\alpha/\alpha$. All transitions were visually checked for obvious cases of blends, and where found, those transitions were discarded. In addition, for the purposes of the preliminary results in this paper, we confine ourselves to using the FeV and NiV transitions listed in Berengut et al. (2013) [14]. However, we use the three new laboratory wavelengths (the Kramida, Tchang-Brillet, and Nave wavelength lists) available for these transitions as discussed above.

We fit the absorption spectra in the normal way, using the Many Multiplet method and the software VPFIT [1] For each object, we initially construct a Voigt profile model (by visual inspection) with a single velocity component (absorption line), including all suitable transitions. We then apply VPFIT to optimise the Voigt profile parameters, including $\Delta\alpha/\alpha$ as a free parameter in the fit. Statistical uncertainties are determined from the diagonal terms of the covariance matrix at the best-fitting solution.

Our analysis is on-going, but shows the preliminary results. These preliminary results serve to highlight the importance of this kind of analysis. However, at this early stage, it would be premature

[1] R. F. Carswell and J. K. Webb, 2015, http://www.ast.cam.ac.uk/~rfc/vpfit.html.

to draw any conclusions about the relationship between $\Delta\alpha/\alpha$ and gravitational potential. We do not include a table of $\Delta\alpha/\alpha$ estimates or a weighted mean for this reason.

A detailed consideration of possible systematic effects is required. The results shown in Figure 1 neglect several possible sources of systematic effects, which may explain this apparent detection of variation in α: imprecise wavelength calibration, long and short range wavelength distortions, and systematic effects in the laboratory wavelengths (despite the new measurements). It is important that these possible sources of bias are investigated. Additionally, these preliminary results include only 9 of the 13 objects in our sample. The remaining four objects (BD + 28°4211, RE-J0623-371, REJ2214-492, and REJ0457-281) represent four of the five best targets for this analysis.

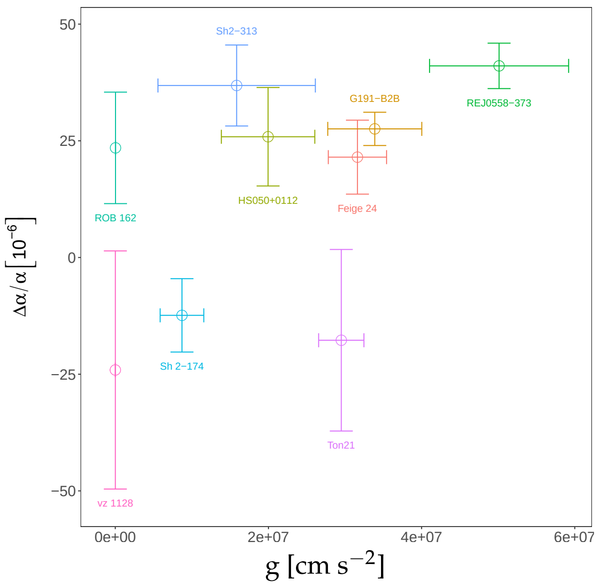

Figure 1. Preliminary $\Delta\alpha/\alpha$ results. Variation in the fine structure constant vs estimated surface gravity, $g = GM/r^2$. For each object in the sample we fitted Voigt profiles simultaneously to the relevant quadruply ionized iron (FeV) and quadruply ionized nickel (NiV) absorption lines of each object and estimated $\Delta\alpha/\alpha$ using VPFIT. Here we show an example of our preliminary results, using the Ward and Nave (2015) [22] laboratory wavelengths. We see a similar trend using the Kramida and Tchang-Brillet wavelength lists. Error bars are 1 σ. The error bars on surface gravity for ROB 162 and vZ 1128 (both sub-dwarf objects) are too small to be seen in this plot.

Studies such as the one summarised here provide a unique way of constraining new ideas in fundamental physics. The equivalence principle is at the heart of general relativity, and it fixes the fundamental constants of nature into an absolute unvarying structure—a structure independent of the material content of the universe. Probing the variation of fundamental constants tests the deepest depths of our current knowledge of physics, with the possibility of illuminating the next frontier of physics. This study is the first statistical sample of constraints on alpha from high-resolution white dwarf spectra. Forthcoming HST observations will enhance that sample and improve the constraints further.

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transitions. V. Dzuba, VF and JKW invented the Many-Multiplet method used in this work and first demonstrated the advantages of this method. JKW, JH, JBH, SPP, JB, V. Dumont provided discussion of methodology and potential systematic effects. MBB wrote the paper. WU provided critical revision of the paper. All authors commented on the manuscript at all stages and approved the final version to be published.

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