

Fundamental Physics from Observations of White Dwarf Stars

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Abstract. Variation in fundamental constants provide an important test of theories of grand unification. Potentially, white dwarf spectra allow us to directly observe variation in fundamental constants at locations of high gravitational potential. We study hot, metal polluted 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 registers as small but measurable shifts in the observed wavelengths of highly ionized Fe and Ni lines when compared to laboratory wavelengths. Measurements of these shifts were performed by Berengut et al (2013) using high-resolution STIS spectra of G191-B2B, demonstrating the validity of the method. We have extended this work by; (a) using new (high precision) laboratory wavelengths, (b) refining the analysis methodology (incorporating robust techniques from previous studies towards quasars), and (c) enlarging the sample of white dwarf spectra. A successful detection would be the first direct measurement of a gravitational field effect on a bare constant of nature. We describe our approach and present preliminary results.

A common feature of attempts to unify the Standard Model of Particle Physics with General Relativity is the prediction of variation in the fundamental constants of

nature (Newton’s constant, G ; proton to electron mass ratio, μ ; fine structure constant, α ; etc). This variation can be 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 prospective theories of Grand Unification.

If fundamental ‘constants’ of nature are described by weak scalar fields then they should vary due to the presence of strong gravitational fields (Magueijo et al. 2002). Flambaum & Shuryak (2008) described how a relationship between α and gravitational potential, through the introduction of a massless scalar field, leads 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 k_α is a dimensionless dependency parameter, M is the mass of the object, r is the radial distance from the objects center and α_0 is the laboratory value of the fine structure constant. However, a non-linear relationship could lead to different and possibly larger effects.

Hot white dwarfs, with high gravitational potential (masses comparable to the sun and radii comparable to Earth) and being typically bright with numerous absorption lines, are ideal for probing the relationship between α and strong gravitational fields. Within the absorption spectra of white dwarfs, variation in α manifests as shifts in the observed wavelengths of absorption lines, when compared to laboratory wavelengths (Dzuba et al. 1999). Fig. 1 illustrates the effect of variation in α on absorption spectra. Absorption spectra from hot white dwarf stars provide a direct observational probe of variation in the fine structure constant, $\Delta\alpha/\alpha$, at high gravitational potential.

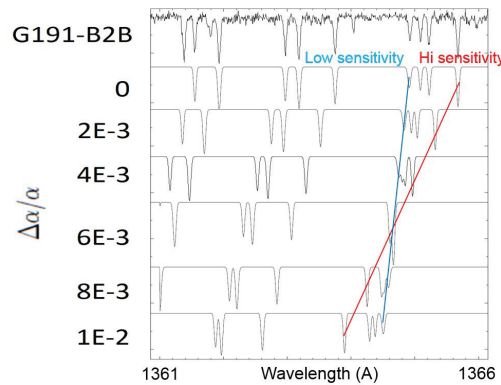


Figure 1. Illustration of wavelength shifts due to variation in the fine structure constant. In the top row we show the G191-B2B *HST/STIS* spectrum. Below we show 6 synthetic spectra, with the 9 FeV absorption lines found in this portion of G191-B2B, simulated with different values of α . The $\Delta\alpha/\alpha$ values used here are exaggerated for illustrative purposes. Each of the 9 transitions have different sensitivities to $\Delta\alpha/\alpha$ and hence different wavelength shifts. The transitions with the highest and lowest sensitivity are indicated by the red and blue lines respectively.

This idea was first tested by Berengut et al. (2013), using *HST/STIS* spectra of the hot DA white dwarf star G191-B2B, where 96 FeV and 32 NiV absorption features were measured. However, the results of this study are inconsistent. When considered separately the FeV absorption yields $\Delta\alpha/\alpha = (4.8 \pm 1.6) \times 10^{-5}$ while the NiV absorption

Table 1. Comparison of sets of laboratory wavelengths. Column 4: average wavelength uncertainty within the range of transitions used in our analysis (1200-1560 Å).

Dataset	Species	Wavelength Coverage [Å]	Unc. [mÅ]	Ref.
Ekberg	FeV	300-530, 1060-1715	4.5	Ekberg (1975)
Raassen	NiV	990-1400	7.0*	Raassen & van Kleff (1976)
Azarov	FeV	647-1185		Azarov et al. (2001)
Kramida	FeV	300-530, 645-1715	2.7	Kramida (2014)
Tchang-Brillet	FeV	1198-1569	2.0	not yet published
Ward	FeV, NiV	1100-1800	3.0	Ward & Nave (2015a)

* - as estimated by Berengut et al. (2013)

yields $\Delta\alpha/\alpha = (-6.1 \pm 5.8) \times 10^{-5}$. Berengut et al. suggest that this inconsistency is due to a systematic effect in the laboratory wavelengths used.

Does the fine structure constant vary within a strong gravitational field? To answer this question we need to improve precision and increase the number of objects being analysed. To do so we have made 3 important improvements to the previous work: (a) We are investigating the proposed systematic effect in the laboratory wavelengths using 3 new independent data sets, (b) we are studying a sample of 13 white dwarfs and sub-dwarfs spanning a wide range of gravitational field strengths (including 3 new observations to be made with the *HST* during Cycle 24), and (c) we have refined the analysis methodology by simultaneously modelling all relevant atomic transitions rather than individual absorption lines.

The systematic effect suspected by Berengut et al. (2013) is an important problem as it is difficult to separate a gain calibration error from a potential wavelength shift due to $\Delta\alpha/\alpha$ (both are dependent on transition wavelength). To address this we are utilising three new sets of independent laboratory wavelengths, in addition to the two data sets (Raassen & van Kleff 1976; Ekberg 1975) used in Berengut et al. Table 1 lists the available sets of laboratory wavelengths for FeV and NiV, within our wavelength range of interest (1000-1800 Å). Kramida (2014) published a revised comprehensive list of laboratory wavelengths based on the measured wavelengths from Ekberg (1975) and Azarov et al. (2001). Between 2014-2015 two of our collaborators, Lydia Tchang-Brillet (LERMA, Paris) and Gillian Nave (NIST, Gaithersburg) together with Edward Ward (University of Arizona), re-observed the FeV spectrum to give us two additional new sets of independent laboratory wavelengths. Both of these have yet to be published, but the NIST dataset has been discussed at various conferences (Ward & Nave 2015a,b, 2016). Using these 3 independent sets we intend to investigate and account for this important systematic effect. However, we already know that the systematic gain calibration error, observed by Berengut et al. (2013), does not appear in the new NIST data set.

We include 13 objects in our sample, listed in Table 2, including 3 new observations that will be obtained with *HST*/STIS during Cycle 24. These objects are known to be polluted with Fe and Ni and they span a wide range of gravitational potentials, allowing us to investigate a wide parameter space and better understand the physics. Nine of the thirteen objects have similar temperatures, between 50 000 K and 65 000 K, en-

Table 2. Characteristics of the white dwarf and sub dwarf sample. Uncertainties are 1σ .

Object	Type	T_{eff} [K]	$\log g$	Ref.
vz 1128	O(H)	$36\,600 \pm 400$	3.9 ± 0.1	Chayer et al. (2015)
ROB 162	O(H)	$51\,000 \pm 2000$	4.5 ± 0.2	Heber & Kudritzki (1986)
BD+28°4211	sdO	$82\,000 \pm 5000$	6.20 ± 0.15	Latour et al. (2013)
Sh 2-174	O(H)	$64\,000 \pm 2900$	6.94 ± 0.16	Good et al. (2005)
Sh2-313	DAO	$80\,000 \pm 10000$	7.2 ± 0.3	Ziegler et al. (2012)
HS0505+0112	DAO	$63\,200 \pm 2100$	7.30 ± 0.15	Good et al. (2005)
Ton21	DA	$69\,710 \pm 530$	7.47 ± 0.05	Barstow et al. (2003)
Feige 24	DA	$60\,000 \pm 1100$	7.50 ± 0.06	Barstow et al. (2003)
G191-B2B	DA	$52\,500 \pm 900$	7.53 ± 0.09	Barstow et al. (2003)
REJ0558-373	DA	$59\,500 \pm 2200$	7.70 ± 0.14	Barstow et al. (2003)
RE-J0623-371*	DA	$58\,200 \pm 1800$	7.14 ± 0.11	Barstow et al. (2003)
REJ2214-492*	DA	$61\,600 \pm 2300$	7.29 ± 0.11	Barstow et al. (2003)
REJ0457-281*	DA	$51\,000 \pm 1100$	7.93 ± 0.08	Barstow et al. (2003)

* - to be observed with *HST*/STIS during Cycle 24

sure that the ion and energy level populations of Fe and Ni mirror those in G191-B2B and allowing reliable comparisons to be made between objects.

Before modelling the absorption lines, we examine the spectral data of each object and determine which FeV and NiV transitions are useful for our analysis. It is important to carefully select what lines contribute to the $\Delta\alpha/\alpha$ analysis for each object, on an individual case by case basis (to avoid blended absorption from other species). For the preliminary results presented in this paper, we confine ourselves to using the FeV transitions tabulated in Berengut et al. (2013). Although, we cannot use all of these transitions in all objects. Each object has a different Fe and Ni abundances (causing the line strength to vary) and different signal-to-noise characteristics (potentially obscuring weak transitions).

We use the software VPFIT¹ to estimate $\Delta\alpha/\alpha$ from the absorption spectra. For each object, we construct an initial Voigt profile model, to all relevant transitions, with a single velocity component (absorption line) and apply VPFIT in the normal way (see the relevant sections of Murphy et al. (2004), King et al. (2012) and Wilczynska et al. (2015)). VPFIT applies non-linear least-squares optimisation of the Voigt profile to the spectral data, including $\Delta\alpha/\alpha$ explicitly as a free parameter. Fig. 2 demonstrates how we use VPFIT to estimate $\Delta\alpha/\alpha$. Statistical uncertainties are determined from the diagonal terms of the covariance matrix at the best-fitting solution. The statistical uncertainties produced by VPFIT have been verified using Markov Chain Monte Carlo simulations (King et al. 2009). VPFIT has been used in the search for $\Delta\alpha/\alpha$ for decades (Webb et al. 2001; Murphy et al. 2004; King et al. 2012; Wilczynska et al. 2015) and applies standard and well-established statistical inference techniques.

Our analysis is on-going but our preliminary results (see Fig. 3) are consistent with no relationship between α and gravitational field strength (Pearson correlation coefficient = 0.003, p-value for the linear regression > 0.99) and with no variation in α (deviation from zero: p-value = 0.71, 0.4σ). However, these preliminary results only utilise the FeV absorption lines and include only 7 of the 13 objects in our sam-

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

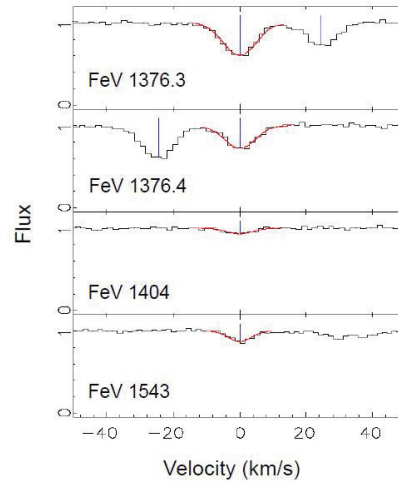


Figure 2. Demonstration of simultaneous modelling using VPFIT. We modelled 4 FeV lines from G191-B2B simultaneously using VPFIT. Shown is the model (red), spectral data (black) and vertical ticks (blue) to indicate velocity components. VPFIT determines the optimal values of the Voigt profile parameters, including the overall photospheric redshift of the object. The photospheric redshift and the wavelength shift due to potential variation in α combine to determine the observed wavelength of each transition. The photospheric redshift is the same for each transition while the wavelength shift due to $\Delta\alpha/\alpha$ is dependent on the sensitivity of the transition to $\Delta\alpha/\alpha$ (quantified by the α sensitivity parameter or q-coefficient) allowing us to estimate $\Delta\alpha/\alpha$.

ple. We expect that the precision of the $\Delta\alpha/\alpha$ estimate from each object will be improved by including NiV. In addition, once we include the remaining 6 objects, we expect to have a clearer picture of the relationship between α and gravity. The analysis of BD+28°4211 and the three new observations from *HST* Cycle 24 (RE-J0623-371, REJ2214-492 and REJ0457-281) are particularly important. BD+28°4211 is one of the two highest signal-to-noise objects currently in our sample, the other being G191-B2B, and we have ensured an optimal resolution and enough exposure time for the three new observations (RE-J0623-371, REJ2214-492 and REJ0457-281) to produce very high signal-to-noise spectra. These 4 objects represent 4 of the 5 best targets for this analysis, with G191-B2B being the optimal target.

A thorough consideration of potential systematic effects is needed. Numerous effects can potentially create a spurious $\Delta\alpha/\alpha$ detection, for example: imprecise wavelength calibration, long and short range wavelength distortions, spectral error arrays and systematics in the laboratory wavelengths. Although, it is important to note the systematic calibration shift observed by Berengut et al. (2013) (Fig. 2) does not appear in the Ward & Nave (2015b) set of laboratory wavelengths.

There is much work yet to be done, so we defer making any conclusions about the relationship between α and gravitational potential at this stage in our analysis, and for this reason we have not provided a table of $\Delta\alpha/\alpha$ estimates or attempted to interpret this result. Despite being incomplete, our analysis is the first study of a relationship between α and gravitational potential using a sample of white dwarf stars. We are confident that our continued analysis will yield significant constraints. A successful detection of a

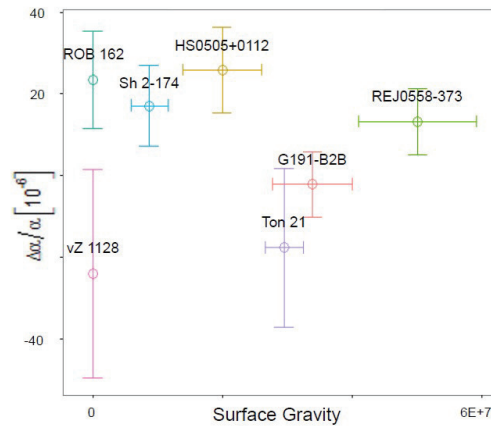


Figure 3. Example of our preliminary results. We simultaneously modelled all relevant FeV transitions using VPFIT, and directly estimated $\Delta\alpha/\alpha$. In this example we used the Ward & Nave (2015a) laboratory wavelengths, we have similar results from the other 3 sets of laboratory wavelengths. The error bars are 1σ and the error bars on surface gravity for the 2 sub-dwarfs (ROB 162 and vZ 1128) are too small to be seen in this plot.

gravity dependence in α would be the first direct measurement of a gravitational field effect on a bare constant of nature.

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