

Astrophysical Probes of Varying Constants and Unification

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Abstract. The observational evidence for the acceleration of the universe demonstrates that canonical theories of gravitation and particle physics are incomplete, if not incorrect. A new generation of astronomical facilities will soon carry out precision consistency tests of the standard cosmological model and search for evidence of new physics beyond it. I describe recent work of CAUP's Dark Side team on some of these tests, focusing on the stability of nature's fundamental couplings and tests of unification scenarios.

1. Varying couplings & Unification

Nature is characterized by a set of physical laws and fundamental dimensionless couplings, which historically we have assumed to be spacetime-invariant. For the former this is a cornerstone of the scientific method, but for the latter it is only a simplifying assumption without further justification. Fundamental couplings are expected to vary in many extensions of the current standard model, including in theories with additional spacetime dimensions, such as string theory. A detection of varying fundamental couplings will be revolutionary: it will immediately prove that the Einstein Equivalence Principle is violated (and therefore that gravity can't be purely geometry), that there is a fifth force of nature, and so on.

Recent astrophysical evidence from quasar absorption systems [1] observed with HIRES/Keck and UVES/VLT suggests a parts-per-million spatial variation of the fine-structure constant α ; although no known model can explain such a result without considerable fine-tuning, there is also no identified systematic effect that can explain it.

In theories where a dilaton-like dynamical scalar field yields varying α , the other gauge and Yukawa couplings are also expected to vary. In Grand Unified Theories, the variations of α are related to those of the proton-to-electron mass ratio μ and the proton gyromagnetic ratio g_p by model-dependent parameters. Specifically [2]

$$\frac{\Delta\mu}{\mu} = [0.8R - 0.3(1 + S)] \frac{\Delta\alpha}{\alpha}, \quad \frac{\Delta g_p}{g_p} = [0.10R - 0.04(1 + S)] \frac{\Delta\alpha}{\alpha}, \quad (1)$$

where R is related to QCD and S is related to electroweak physics. This parametrization is valid for any model where gauge coupling unification occurs at some (unspecified) high energy scale. Thus joint measurements of these couplings in various systems can provide key consistency tests.

This approach has been used in [2] for BBN, [3] for Population III stars and in [4] for the Sun. Here we report on analogous work for neutron stars [5] and quasar absorption systems [6], as well as for laboratory measurements using atomic clocks [7].



2. Neutron Stars

We can exploit the complementarity provided by the extreme conditions of matter described by the nuclear equation of state (EoS) in heavy ion and neutron star physics. Although the precision of inferred nuclear observables is much lower than for BBN, one can assess the constraining power of these high density environments and scan the (α, R, S) parameter space.

For this we choose a physically motivated set of equations of state for dense matter [5] and, for the purposes of this poster, assume a variation of $\Delta\alpha/\alpha = 5 \times 10^{-3}$. This is larger than suggested by [1], but that value holds for very low density systems (absorption lines along the line of sight of quasars) and in the context of environment-dependent variations will not apply to high-density environments. We note that our analysis differs from that of [2] where some unification models were studied, by choosing fixed values of α , R and S . Here our goal is to scan the phenomenological (R, S) space for fixed choices of α .

The EoS of nuclear matter is crucial for describing neutron star structure and, in particular, to obtain its mass-radius relationship. This same EoS is also relevant for understanding the properties of nuclei and yields of heavy ion collisions (at higher temperatures) experimentally accessible on Earth. The possible variation of masses of different population species under beta equilibrium, namely nucleons and electrons, can be modified by the non vanishing values of a variation in α . There is a vast number of model EoSs in the literature.

In [5] we focused on parametrizations such as TM1, and we have verified that more advanced parameterizations as PK1 yield same trend results. In order to partially account for the spread of the nuclear EoS we introduce a phenomenological parameter δ to parameterize the softness of the EoS: for $0 \leq \delta \leq 0.5$ the pressure is modified as $P(1 - \delta)$. Since our reference EoS describes better the stiff side of the constraints, $\delta \geq 0$. The unchanged TM1 EoS describes the neutron rich systems and as $\delta > 0$ more isospin symmetric systems can be accessed. With this procedure we partially size the combined effect of the uncertainty in the isospin content and the softness of the EoS and the robustness of our findings.

In Fig. 1 we plot values of R and S yielding pressure values compatible with EoS from neutron star constraints (using the TM1 EoS) as well as from heavy ion collision data (both for symmetric nuclear matter and pure neutron matter). We see that, globally, allowed values lie on a variable-width strip. Without being fully comprehensive on the scan of the allowed R and S values we can see that equally stiff or soft EoS have constraining power in their phase space.

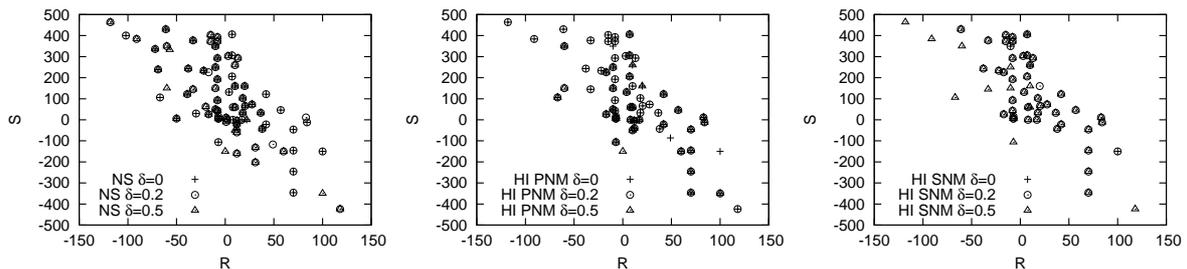


Figure 1. R, S phase space exclusion region. Crosses, circles and triangles denote values of pressure compatible with neutron star (left) and heavy ion symmetric nuclear matter (middle) and pure neutron matter (right) constraints when applying a spread of $\delta = 0, 0.2, 0.5$ for $\Delta\alpha/\alpha = 5 \times 10^{-3}$.

One must note that the experimental uncertainties here are much larger than in the low density BBN case. Nevertheless in all cases we studied the tendency is the same, showing robustness, and we find that the allowed region in the (R, S) plane partially overlaps the values allowed by BBN and in particular the 'typical' values $R \sim 30$ and $S \sim 160$ [2].

3. Atomic Clocks and QSOs

By measuring the rate of two different atomic clocks one obtains a constraint on the relative shift of the corresponding characteristic frequencies. These are proportional to certain products of fundamental couplings, and thus the measurement can be translated into a constraint of the drift of that combination. Different clock comparisons are sensitive to different products of these couplings, and therefore a combined analysis of all existing measurements, summarized in [7], leads to constraints on each of them.

From this analysis we obtain the following 68% confidence intervals

$$\frac{\dot{\mu}}{\mu} = (6.8 \pm 26.3) \times 10^{-17} \text{ yr}^{-1}, \quad \frac{\dot{g}_p}{g_p} = (-7.2 \pm 4.4) \times 10^{-17} \text{ yr}^{-1}. \quad (2)$$

These should be compared to the result of [8] for the fine-structure constant (also at the 68% confidence level)

$$\frac{\dot{\alpha}}{\alpha} = (-1.7 \pm 2.3) \times 10^{-17} \text{ yr}^{-1}. \quad (3)$$

This highlights the importance of improved experimental bounds using pairs of clocks with different sensitivities to α , μ and g_p .

The above formalism can be used to obtain constraints on the $R - S$ parameter space, shown the left panel on Fig. 2. There is a degeneracy between the two, so that only a combination of them is well constrained. The degeneracy direction is $(S + 1) - 2.7R = -5 \pm 15$, and the naively expected values are allowed. By separately fixing each of them we find

$$R = 61 \pm 71, \quad \text{assuming } S = 160 \quad (4)$$

$$S = 76 \pm 197, \quad \text{assuming } R = 30. \quad (5)$$

An analogous study can be made using existing astrophysical measurements of combinations of the fine-structure constant α , the proton-to-electron mass ratio μ and the proton gyromagnetic ratio g_p towards the radio source PKS1413+135, at redshift $z \sim 0.247$ [6]. In this case one finds (at the one-sigma confidence level)

$$\frac{\Delta\alpha}{\alpha} = (-5.1 \pm 4.3) \times 10^{-5} \quad (6)$$

$$\frac{\Delta\mu}{\mu} = (4.1 \pm 3.9) \times 10^{-5} \quad (7)$$

$$\frac{\Delta g_p}{g_p} = (9.9 \pm 8.6) \times 10^{-5}; \quad (8)$$

these constraints are still relatively weak, and in particular do not yet provide a test of the dipole result [1]. However, improvements of one order of magnitude in each of the combined measurements (which are well within the reach of forthcoming facilities) should turn this into a stringent test. Moreover, the current results are intriguing when translated into the $R - S$ plane, as shown in the right panel of Fig. 2.

From this analysis we obtain the best-fit values for R and S at the one-sigma confidence level

$$R = 277 \pm 24, \quad S = 742 \pm 65. \quad (9)$$

Although the notion that there is a 'standard' model for unification is debatable, it is worth noticing that these values are significantly different from the suggested $R \sim 30$ and $S \sim 160$. A discussion of the causes and implications of this result is beyond the scope of the present work.

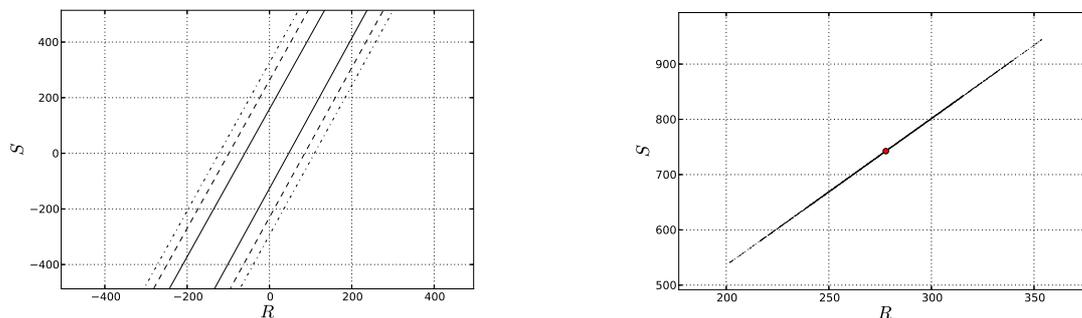


Figure 2. Regions in the R, S parameter space in agreement with current tests of the stability of fundamental constants, from local measurements with atomic clocks (left) and from astrophysical measurements towards the radio source PKS1413+135 (right). Solid, dashed and dotted lines correspond to 68.3%, 95.4% and 99.97% likelihood contours, respectively.

4. Conclusions

Our results show the potential for using the high density region of the density phase space of matter to constrain fundamental physics *in addition* to low density tests using BBN and the CMB. Both our high-density and our atomic clock results are compatible with theoretical expectations on unification scenarios, but much freedom exists (especially in the latter case) due to the presence of a degeneracy direction in the relevant parameter space.

This degeneracy persists for astrophysical measurements towards the radio source PKS1413+135, but in this case the preferred values shift significantly, and are no longer compatible with (arguably naive) expectations on unification. Our analysis motivates the interest of further, more precise astrophysical measurements of fundamental couplings in this and other astrophysical systems.

Finally, this ongoing project highlights the point that the early universe is an ideal laboratory in which to carry out precision consistency tests of our standard cosmological paradigm and search for and constrain new physics. Future facilities such as ALMA, the E-ELT, the SKA and other will play a key role in this endeavour. Future work to explore the relevant parameter space and break parameter degeneracies by combining measurements from systems with different $R-S$ sensitivities is needed.

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