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Is the fine-structure constant not actually constant?

Clarifying the concept of entanglement

Trapped atomic ions and precision sensing

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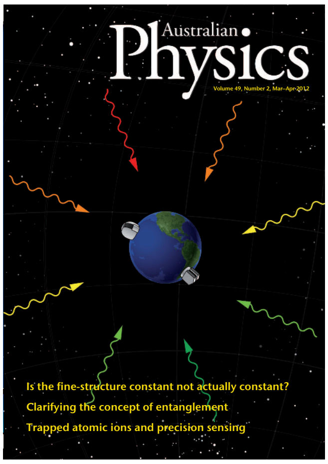

Cover

Observations of the northern sky from Hawaii and observations of the southern sky from Chile have now been combined to provide evidence that the fine-structure constant varies across the Universe – see the article by Michael Murphy on page 43 [credit: Julian Berengut, University of NSW].

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Electromagnetism: Does Its Strength Vary Across the Universe?

Michael Murphy

The fundamental constants are central to our theories of physics, yet those theories offer no understanding of the constants, no way to calculate them. If the constants were found to vary, we might learn what they depend on and perhaps glimpse a more fundamental theory, perhaps 'the' theory. For a decade we've found that α, the fine-structure constant, which characterises electromagnetism's strength, is slightly smaller in distant galaxies, at least those appearing in the northern sky, than on Earth. But now, with measurements over both hemispheres, we find evidence for a dipole-like variation in α across the sky. The fine-structure constant α could be the first fundamental constant that isn't.

Fundamental? Constants?

To many physics undergraduates, the fundamental constants of Nature must seem little more than a rather long list of obscure numbers at the back of their textbooks. Annoyingly, they have to be committed to memory, not quickly re-derived in a side-calculation as physicists would prefer to do. And they're (irrational) real numbers, not nice, easy-to-remember, round ones – how many digits of Planck's constant can you rattle off without googling 'h'?

But these inconveniences go much deeper, right to the heart of our current understanding of physics, in fact. Richard Feynman said it best (as usual) about $\alpha = e^2/\hbar c$, the fine-structure constant of electromagnetism:

"It has been a mystery ever since it was discovered… and all good theoretical physicists put this number up on their wall and worry about it. Immediately you would like to know where this number for a coupling comes from: is it related to pi or perhaps to the base of natural logarithms? Nobody knows. It's one of the greatest damn mysteries of physics… We know what kind of a dance to do experimentally to measure this number very accurately, but we don't know what kind of dance to do on the computer to make this number come out, without putting it in secretly!" [1].

That is, within current physics theories, an expression for any observable quantity inevitably includes at least one fundamental constant, the value of which is known only from experiment. The constants cannot be derived within the theories; hence the title 'fundamental' and the annoying need to commit them to memory. Similarly, the theories say nothing about their constancy – only experiments can establish that or rule it out. So far, some of the most staggeringly precise laboratory measurements ever made have not revealed any variability (e.g. [2]).

And why so many fundamental constants to 'worry about'? Probably because our current theories don't describe the most fundamental physics, but merely a set of approximate physical laws. Much like the Newtonian concept of gravity is fundamentally incorrect and Einstein's general relativity is better, probably our current concept of all physical laws is fundamentally incorrect. The aim,

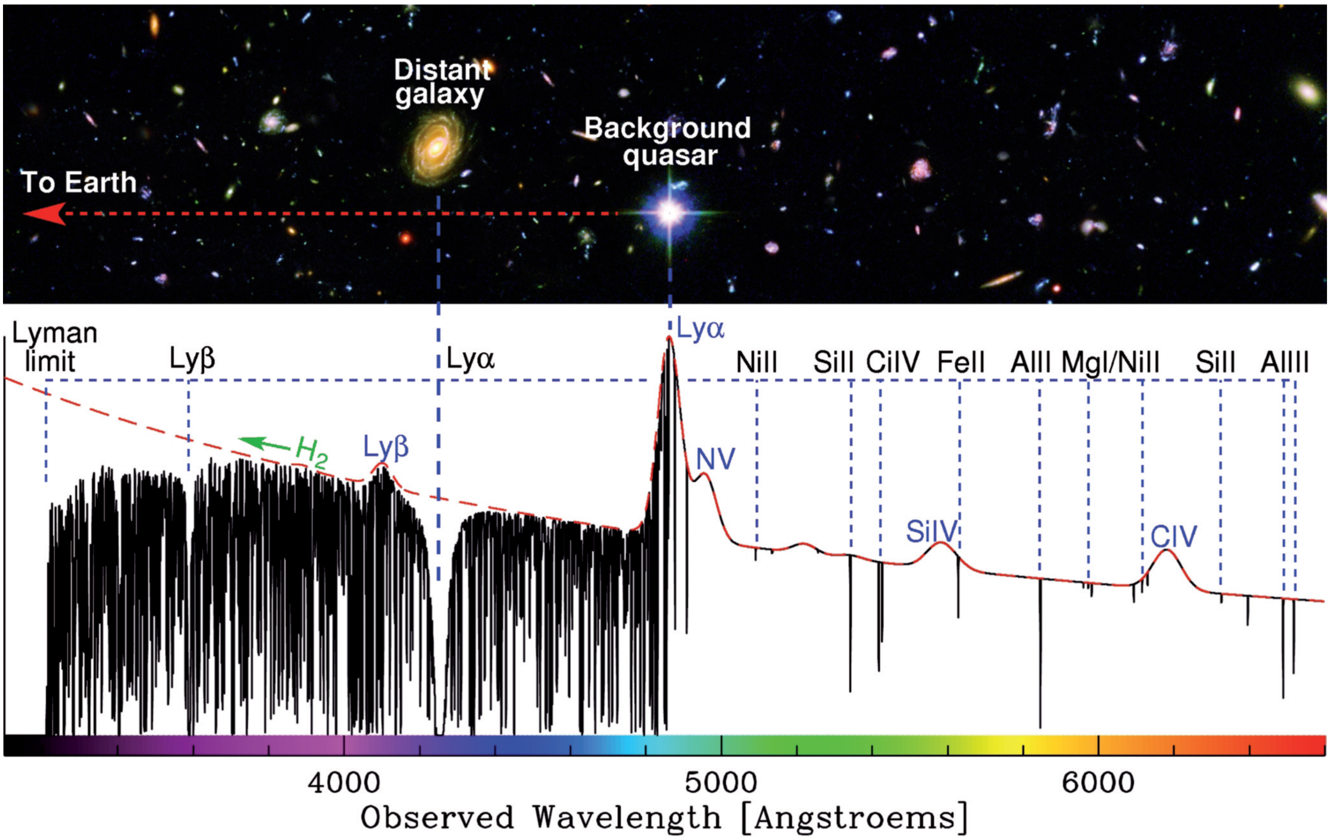

Fig. 1. The quasar absorption line experiment. The top panel shows quasar light intersecting a galaxy on its way to Earth. The bottom panel shows a synthetic (but realistic) quasar spectrum with important emission lines (blue labels) from the quasar and absorption lines (black & green labels) from the intervening galaxy. The relative separations between the metal lines are sensitive to the fine-structure constant α.

of course, is to find a better theory, maybe 'the correct one', maybe one without seemingly arbitrary fundamental constants.

The search for 'variable constants' is therefore a basic test of physics beyond the Standard Model. But beyond-Standard theories currently offer little to guide where and when in the Universe any variability is strongest, or easiest to spot. We therefore need to test the variability of fundamental constants in as wide a variety of places and times in the Universe as possible.

α, quasars and the Many Multiplet method

The time variability of α has, of course, been scrutinised in highly controlled, Earth-bound laboratory experiments. The degree to which frequencies of electromagnetic transitions depend on α varies from transition to transition, ion to ion. By comparing the ticking rates of single-ion optical atomic clocks based on Al and Hg over 10 months, the relative rate of change in α was recently limited to just a few parts in 10^{17} per year [2]. Impressive, certainly, but what if α changes, say, non-linearly with time and you want to know its value in a far-flung galaxy 10 billion light-years away? Without a theory of varying α, that 10-month laboratory experiment in our little corner of the Universe can't say much about the laws of physics across the entire Universe and throughout its 14 billion year history.

Quasars, and the odd 10-m diameter telescope, make looking back 10 billion years routine. Quasars are supermassive ($\sim 10^9$ solar mass) black holes at the centre of galaxies. Friction and gravitational energy from an accretion disc of in-falling gas and dust means quasars outshine all the stars in their host galaxies, radiating $\sim 10^{40}$ W of light which, even 10 billion light-years away, appears as a relatively bright, star-like continuum of radiation in our sky – see Fig. 1.

While quasars are obviously interesting in themselves, ripe with extreme physics and complex interactions with their host galaxies, their brightness, distance, compactness and spectral simplicity (no narrow features) also make their lines-of-sight to Earth perfect probes of the narrow absorption lines from intervening gas. Fig. 1 shows the (simulated) spectrum of a quasar and labels the absorption lines. Most arise from the Lyman α transition of neutral hydrogen in the pervasive intergalactic medium, causing a 'Lyman α forest' bluewards of (at lower redshifts than)

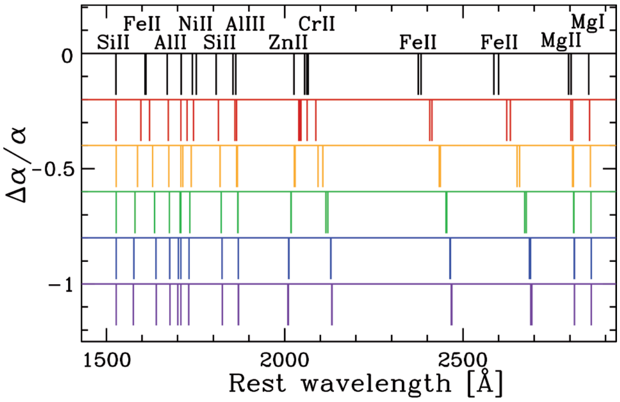

Fig. 2. Sensitivity to α variation of metallic transitions seen in quasar absorption systems. Here Δα/α is the relative deviation in α from the current laboratory value, while 'I' denotes a neutral species, and 'II', 'III' denote singly- and doubly-ionised species. Note that the redder Fe and Mg transitions have a very different pattern of shifts to the bluer transitions; low- and high-redshift absorption systems respond very differently to systematic effects.

the quasar's Lyman *α* emission line. But the line of sight to many quasars also passes near enough to a distant galaxy to produce a deep, damped Lyman *α* line, a Lyman ionisation edge, molecular hydrogen bands (sometimes) and, most importantly for us, narrow metallic absorption lines.

It's these metal lines from intervening gas clouds towards background quasars that provide the best (optical) probe of cosmological variations in *α*. Their sensitivity to *α* is shown in Fig. 2. This figure is the essence of the so-called 'Many Multiplet' method: like a barcode, the relative wavelength separations of transitions from different multiplets, and different ions, encode the value of *α*. Thus, by comparing the pattern of separations seen in a quasar spectrum with laboratory standards, any difference in *α* between a distant gas cloud and the laboratory can be measured.

It's worth noting that the set of transitions observed in any given quasar spectrum, from any given absorption system, varies considerably. Looking back at Fig. 2, this means that the pattern of wavelength shifts from the laboratory standards will be different from one absorber to another; each one has a different barcode depending on which transitions are observed. From the point of view of minimising systematic effects, this is very much a good thing: most instrumental systematics one can imagine tend to affect all quasar spectra in the same general ways, so different barcodes will be affected in different ways by such systematics. That is, the diversity of transitions observed in different absorption systems helps to average over and/or expose simple systematic errors.

A stubborn result: smaller α in quasar absorbers

The Many Multiplet method of analysing quasar spectra for the variability of *α* was proposed and first demonstrated [3, 4] in 1999 by John Webb, Victor Flambaum and Vladimir Dzuba at the University of New South Wales. At that time, the first largish samples of high-quality, high-resolution spectra were coming from the 10-metre diameter Keck Telescope in Hawaii. Even with a sample of 30 absorption systems, there was an indication that *α* was smaller in the absorption clouds, on average, than in the laboratory by about 10 parts per million, with a statistical significance of about 3σ [4]. Only the redder Fe and Mg lines could be used in those spectra – those on the right of Fig. 2 – and, consequently, the absorption redshifts were all below 1.8, placing the transitions in the visible observing window.

Many 3σ results go away, usually quite quickly. Not through lack of attention, this result didn't... and still hasn't. Its first test was at higher redshifts where, as you'll note in Fig. 2, an entirely different pattern of line shifts was expected. But we saw the same result [5, 6]: a smaller *α* in the absorption clouds by about 7 parts per million at redshifts 1.8–3.3, the same as the (re-analysed) lower redshift results. Combined, they constituted 4σ evidence of *α* varying on cosmological scales.

> **"The fine-structure constant α could be the first fundamental constant that isn't."**

A larger sample added in 2002, this time covering both low and high redshifts, gave the same result as the previous two datasets [7]. By 2004 we had published 143 measurements of *α* in distant galaxies with the consistent result that *α* was about 6 parts per million smaller than the current laboratory value [8]. The formal statistical significance of the evidence for varying *α* was now above 5σ.

So the signal had not disappeared with added data. Indeed, it had become clearer, as one expects from a real variation in *α*... or, of course, a well-defined systematic error. For an observational (rather than experimental) result like ours, this is, and remains, the most difficult question to answer: can systematic errors explain it?

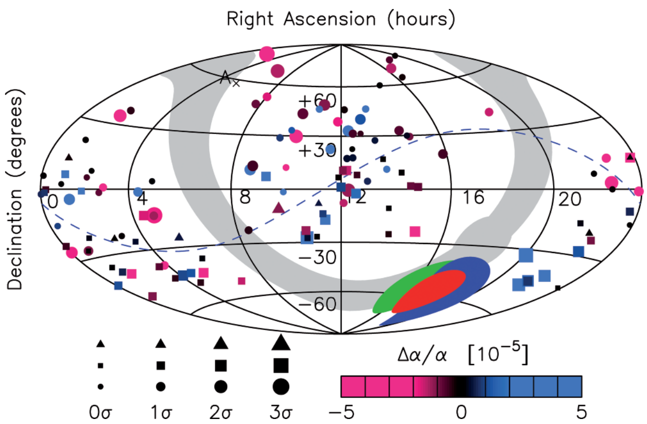

Fig. 3. Distribution of Δα/α values from Keck (circles), VLT (squares) and both telescopes (triangles) across the sky. The relative deviation from the laboratory value is colour-coded, while the point size scales with the significance of that deviation. The grey band indicates the Milky Way disk, behind which few bright quasars are known. The red blob near the Galactic centre (grey bulge) is the direction and 1σ contour of a dipole fitted to all Δα/α measurements, while the green and blue blobs are the dipole directions fitted to the Keck and VLT data independently. The cross marked 'A' and the blue dashed curve indicate the Keck + VLT dipole's anti-pole and equator, respectively. Weighted mean values were used for quasar lines of sight with two or more absorption systems.

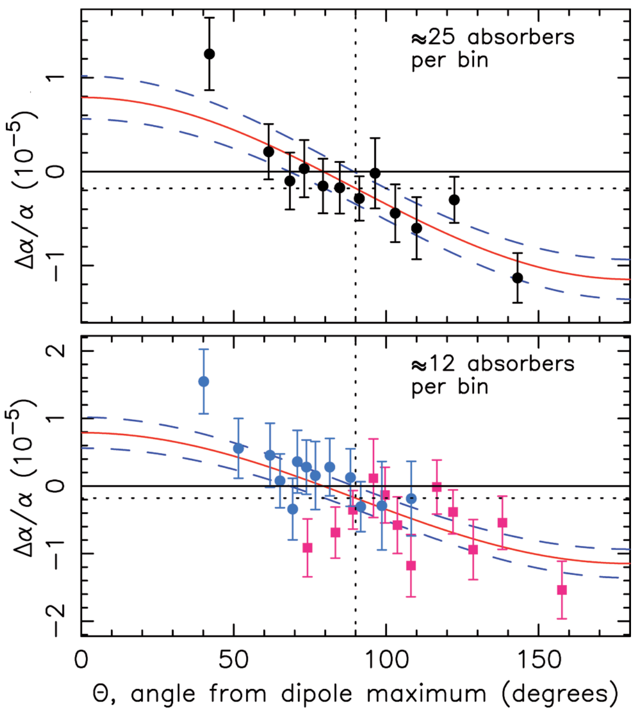

Fig. 4. Binned values of Δα/α versus the angle from the best-fitting dipole direction. The bottom panel separates the Keck (pink) from the VLT (blue) values, while the top panel combines them. The red line indicates the best-fitting dipole model, while the blue dashed line shows its 1σ error.

One by one, we analysed and ruled-out or limited the effect of many possible astrophysical and instrumental systematic errors [7, 9]. None could explain what we'd found.

However, all the indications for a varying α had so far come from just one telescope, the Keck Telescope in Hawaii. No matter how good the Keck is, no-one should trust a fundamental result like this from just a single instrument. Enter the VLT – the Very Large Telescope – in Chile.

New result: an α dipole?

In 2004 we began the long task of compiling a similarly large sample of high-quality, high-resolution quasar spectra from the VLT. The previous Keck data were generously donated to us (see the Acknowledgments) already 'reduced' from their raw form taken at the telescope into analysis-ready, science-grade quasar spectra. The VLT spectra had to be reduced from scratch. We also discovered problems with the way VLT spectra were wavelength calibrated – the crucial calibration step when looking for shifts between absorption lines – and these needed to be overcome [10]. But with the hard work of PhD student Julian King at UNSW, we began measuring α in 153 absorption systems in 2008, over the same redshift range, using the same Many Multiplet method as before.

In my mind, there were two likely possibilities: The VLT would show no variation in α, or it would give the same, smaller value of α in the absorbers as the Keck data. Neither was true. Nor was it something in between. In fact, the VLT spectra showed the *opposite* variation in α to the Keck spectra! That is, on average, the VLT values of α were *larger* in the absorbers than the current laboratory value [11, 12].

Your immediate reaction is probably similar to mine: the VLT results simply disagree with the Keck results, neither are correct, and both are the product of (probably different) systematic effects. Well, we had not found a simple systematic error that explained the Keck results and it is similarly difficult to explain the VLT results by a systematic error. Explaining both away probably requires two different systematic errors. But, I'm sure you say, this is still the most likely answer. Maybe.

There's another possibility. We projected the results onto the sky, as in Fig. 3. The Keck and VLT see different skies on average – Keck is at +20° latitude and the VLT is at –25°. Our Keck quasars were predominantly northern ones, our VLT quasars predominantly southern, but many in both samples were equatorial. In Fig. 3 you notice a tendency for larger blue squares – greater positive deviations

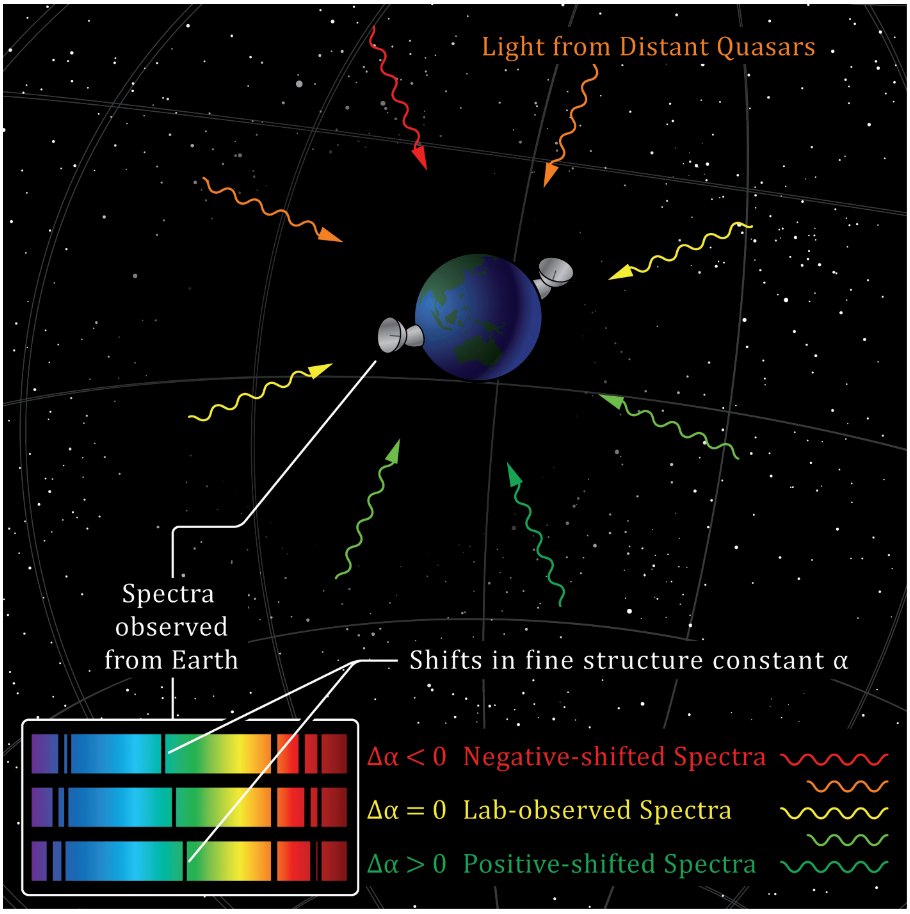

Fig. 5. Illustration of the α dipole and the spectral line shifts (see also Fig. 2) which are observed, on average, over many quasar lines of sight from two different telescopes, the Keck and the VLT. [credit: Julian Berengut, UNSW]

"The aim, of course, is to find a better theory, maybe 'the correct one', maybe one without seemingly arbitrary fundamental constants."

in α from the laboratory value – to appear near the bottom right of the plot, and larger pink circles to appear near the top left, indicating larger negative deviations. In the middle you notice a mix of smaller symbols, ie. less significant deviations from the laboratory value. The data seem to suggest variation in α across the sky!

Modelling α as a dipole on the sky (ignoring any redshift dependence for now), we can show in Fig. 4 the deviation in α as a function of angle from the best-fitting dipole direction. The dipole model does seem to describe the data very well. Indeed, compared to a monopole model (ie. constant offset in α in all directions), the dipolar variation in α is significant at 4σ, as assessed by both analytical means and by a bootstrap technique (ie. randomly reassigning α measurements to different quasar sight-lines) [11, 12].

The dipole direction is shown as a red 1σ error blob in Fig. 3. Because it's deep in the southern hemisphere, you may still suspect that the apparent dipolar variation in α is driven by systematic effects *between* the two different telescopes, Keck and VLT, even though they agree for equatorial regions. But the blue and green blobs in Fig. 3 give significant pause for thought: when dipoles are fitted to the Keck and VLT data independently, they point in the same direction on the sky. If the dipolar variation from the combined results was driven by systematic errors between Keck and VLT, you would not expect this. We estimate such close alignment would happen 6% of the time by chance alone, given the distribution of quasar sight-lines across the sky [11, 12].

We also find similarly-close alignment between dipoles fitted independently to low- and high-redshift subsamples of the combined Keck + VLT results, with a 2% chance of occurring by chance alone. The joint probability of both these chance alignments happening is difficult to estimate, but a bootstrap technique suggests that it's about 0.1% [11, 12]. All in all, the current data leave us with the strange picture of the Universe illustrated in Fig. 5.

Conclusions and future tests

After a decade of finding α to be ~6 parts per million times smaller than on Earth in distant galaxies, predominantly in the northern sky, we now find the opposite result on the other side of the sky. But, rather than contradicting each other, these two results show a remarkable consistency: there is 4σ evidence for a dipole-like variation in α across the sky; the dipoles from the two telescopes coincide; the low- and high-redshift dipoles also coincide. And we still have not found systematic errors that can

“After a decade of finding α to be ~6 parts per million times smaller than on Earth in distant galaxies, predominantly in the northern sky, we now find the opposite result on the other side of the sky.”

explain the results from either telescope, let alone the combined results.

I have not mentioned other constraints on variations in α from work by other groups using the Many Multiplet method, or from radio and millimetre-wave absorption lines, or from meteoritic analysis, or from the Oklo natural fission reactor, etc. While none of these other methods has yielded evidence for a varying α, they are all consistent with the α dipole from our work [13].

Dedicated observing programs on both Keck and the VLT are now aimed directly at refuting or confirming our results. And we are starting to target the anti-pole of the dipole with quasars high in the northern sky and near our Galaxy's anti-centre (see Fig. 3): the signal is largest there and even a modest sample could rule it out (or confirm it!). Crucially, we are trying to do this with two telescopes to make absolutely sure that systematic errors are not responsible for whatever we find.

What if all these future astronomical measurements confirm that α varies on cosmological scales? It would still be important to test with a different technique altogether. And laboratory atomic clock experiments may be the key test. We see tentative evidence for the amplitude of the α dipole increasing radially outwards from Earth, supporting a ‘simple' picture of an ‘α gradient' in the Universe [11, 12]. If such a gradient exists in our Solar System, it may be detected as an annual modulation in the relative ticking rates of atomic clocks at the 10^{-20} level [13]. While this is three orders of magnitude below current sensitivity, the last decade has already seen a 1000-fold improvement. With such rapid progress, a laboratory test may see a varying α in the next decade or two.

Acknowledgments

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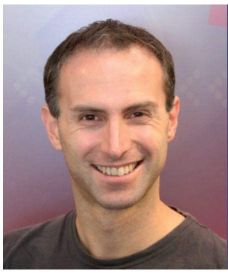

BIO

Michael Murphy is an Associate Professor at Swinburne University of Technology's Centre for Astrophysics and Supercomputing. He received his PhD in physics at the University of New South Wales and spent five years at the University of Cambridge (UK) as a Research Fellow. He returned to Australia in 2007 as a lecturer at Swinburne and began an ARC QEII Fellowship there in 2008. He studies quasar absorption lines and the distant galaxies that cause them.