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# Cosmology with varying constants

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The idea of possible time or space variations of the 'fundamental' constants of nature, although not new, is only now beginning to be actively considered by large numbers of researchers in the particle physics, cosmology and astrophysics communities. This revival is mostly due to the claims of possible detection of such variations, in various different contexts and by several groups. I present the current theoretical motivations and expectations for such variations, review the current observational status and discuss the impact of a possible confirmation of these results in our views of cosmology and physics as a whole.

**Keywords:** cosmology; extra dimensions; fundamental constants; laboratory and astrophysical tests

## 1. Introduction

One of the most valued guiding principles (or should one say beliefs?) in science is that there ought to be a single, immutable set of laws governing the Universe and that these laws should remain the same everywhere and at all times. In fact, this is often generalized into a belief of immutability of the Universe itself—a much stronger statement that does not follow from the former. A striking common feature of almost all cosmological models throughout history, from ancient Babylonian models through the model of Ptolemy and Aristotle to the much more recent 'steady-state model', is their immutable character. Even today, a non-negligible minority of cosmologists still speaks in a dangerously mystic tone of the allegedly superior virtues of 'eternal' or 'cyclic' models of the Universe.

It was Einstein (who originally introduced the cosmological constant as a 'quick fix' to preserve a static universe) who taught us that space and time are not an immutable arena in which the cosmic drama is acted out, but are in fact part of the cast—part of the physical Universe. As physical entities, the properties of time and space can change as a result of gravitational processes. Interestingly enough, it was soon after the appearance of general relativity, the Friedman models and Hubble's discovery of the expansion of the Universe (which shattered the notion of immutability of the Universe) that time-varying fundamental constants first appeared in the context of a

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complete cosmological model (Dirac 1937), though others before him (starting with Kelvin and Tait) had already entertained this possibility.

From here onwards, the topic remained somewhat marginal, but never disappeared completely, and even The Royal Society organized a Discussion on this theme about 20 years ago. The proceedings of this discussion (McCrea & Rees 1983) still make very interesting reading today—even if, in the case of some of the articles, only as a reminder that concepts and assumptions that are at one point uncontroversial and taken for granted by everybody in a given field can soon afterwards be shown to be wrong, irrelevant or simply ‘dead-ends’ that are abandoned in favour of an altogether different approach.

As usual, despite the best efforts of a few outstanding theorists, it took some observational hints for possible variations of the fundamental constants (Webb *et al.* 1999) to make the alarm bells sound in the community as a whole and start convincing some previously sworn sceptics. In the past two years there has been an unprecedented explosion of interest in this area, as large as (or perhaps even larger than) the one caused by the evidence for an accelerating Universe provided by type-Ia supernovae data. On one hand, observers and experimentalists have tried to reproduce these results and update and improve other existing constraints. On the other, a swarm of theorists has flooded scientific journals with a whole range of possible explanations.

Here I will provide a brief summary of the current status of this topic. Rather than go through the whole zoo of possible models (which would require a considerably larger space, even if I were to try to separate the wheat from the chaff), I will concentrate on the model-independent aspects of the problem, as well as on the present observational status. In the final section, I will provide some reflections on the impact of a future confirmation of these time variations in our views of cosmology and physics as a whole.

## 2. On the role of the constants of nature

The so-called fundamental constants of nature are widely regarded as some kind of distillation or ‘executive summary’ of physics. Their dimensions are intimately related to the form and structure of physical laws. Almost all physicists (and even engineers) will have had the experience of momentarily forgetting the exact expression of a certain physical law, but quickly being able to re-derive it simply by resorting to dimensional analysis. Despite their perceived fundamental nature, there is no theory of constants as such. How do they originate? How do they relate to one another? How many are necessary to describe physics? None of these questions has a rigorous answer at present. Indeed, it is remarkable to find that different people can have so widely differing views on such a basic and seemingly uncontroversial issue. Duff *et al.* (2002) have a very interesting discussion of this issue.

One common view of constants is as asymptotic states. For example, the speed of light  $c$  is (in special relativity) the maximum velocity of a massive particle moving in flat space-time. The gravitational constant  $G$  defines the limiting potential for a mass that does not form a black hole in curved space-time. The reduced Planck constant  $\hbar \equiv h/2\pi$  is the universal quantum of action (and hence defines a minimum uncertainty). Similarly, in string theory there is also a fundamental unit of length (the characteristic size of the strings). So for any physical theory we know of, there

should be one such constant. This view is acceptable in practice, but unsatisfactory in principle, mainly because it does not address the question of the constant's origin.

Another view is that they are simply necessary (or should one say 'convenient'?) inventions; that is, they are not really fundamental but simply ways of relating quantities of different dimensional types. In other words, they are simply conversion constants that make the equations of physics dimensionally homogeneous. This view, first clearly formulated by Eddington (1939), is perhaps at the origin of the tradition of absorbing constants (or 'setting them to unity', as it is often colloquially put) in the equations of physics. This is particularly common in areas such as relativity, where the algebra can be so heavy that cutting down the number of symbols is a most welcome measure. However, it should be remembered that this procedure cannot be carried arbitrarily far. For example, we can consistently set  $G = h = c = 1$ , but we cannot set  $e = \hbar = c = 1$ , since then the fine-structure constant would have the value  $\alpha \equiv e^2/(\hbar c) = 1$ , whereas in the real world  $\alpha \sim 1/137$ .

In any case, one should also keep in mind that the possible choices of particular units are infinite and always arbitrary. For example, the metre was originally defined as the distance between two scratch marks on a bar of metal kept in Paris. Now it is defined in terms of a number of wavelengths of a certain line of the spectrum of a  $^{83}\text{Kr}$  lamp. This may sound much more 'high-tech' and rigorous, but it does not really make it any more meaningful.

Perhaps the key point is the one recently made by Veneziano in Duff *et al.* (2002): there are units that are arbitrary and units that are fundamental, at least in the sense that, when a quantity becomes of order unity in the latter units, dramatic new phenomena occur. For example, if there was no fundamental length, the properties of physical systems would be invariant under an overall rescaling of their size; so atoms would not have a characteristic size, and we would not even be able to agree on which unit to use as a 'metre'. With a fundamental quantum unit of length, we can meaningfully talk about short or large distances. Naturally, we will do this by comparison with this fundamental length. In other words, 'fundamental' constants are fundamental only to the extent that they provide us with a way of transforming any physical quantity (in whichever units we have chosen to measure it) into a pure number whose meaning is immediately unambiguous.

Still, how many really 'fundamental' constants are there? Note that some so-called fundamental units are clearly redundant: a good example is temperature, which is simply the average energy of a system. In our everyday experience, it turns out that we need three and only three such units: a length, a time and an energy. However, it is possible that in higher-dimensional theories (such as string theory, see § 4) only two of these may be sufficient. And maybe, if and when the 'theory of everything' is discovered, we will find that even fewer than two are required: again, refer to Duff *et al.* (2002) for a more detailed discussion.

### 3. Standard cosmology: what we know and what we do not

Cosmology studies the origin and evolution of the Universe and in particular its large-scale structures, on the basis of physical laws. By large-scale structures I mean scales of galaxies and beyond. This is the scale where interesting dynamics is happening today (anything happening on scales below this is largely irrelevant for cosmological dynamics). The standard cosmological model, which was gradually put together

during the 20th century, is called the ‘hot Big Bang’ model. Starting from some very simple assumptions, it leads to a number of predictions that have been confirmed observationally.

Three of these predictions are particularly noteworthy. Firstly, there is Hubble’s law: the fact that the Universe is expanding and galaxies are moving away from each other with a speed that is approximately proportional to the distance separating them. Secondly, Big Bang nucleosynthesis (BBN) predicts the relative primordial abundances of the light chemical elements (which were synthesized in the first three minutes of the Universe’s existence): roughly 75% hydrogen, 24% helium and only 1% other elements. Last but not least, there is the cosmic microwave background (CMB). This is a relic of the very hot and dense early Universe. By measuring photons coming from all directions from this background, one finds an almost perfect black-body distribution with a present temperature of only 2.725 K, corresponding to a present radiation density of about 412 photons per cubic centimetre (whereas the present matter density of the Universe is only about three atoms per cubic metre).

However, despite these and many other successes, the model also has a few shortcomings. These should really be seen not as failures of the model, but rather as relevant questions to which the Big Bang model can provide no answer. I will briefly mention two of them. The first arises when, instead of analysing all CMB photons together, one does the analysis for every direction of the sky. This was first done by the Cosmic Background Explorer (COBE) satellite and then confirmed (with increasing precision) by a number of other experiments. One finds a pattern of very small temperature fluctuations, of about one part in ten thousand relative to the 2.725 K. It turns out that CMB photons ceased interacting with other particles when the Universe was about 300 000 years old. After that, they basically propagate freely until we receive them.

Now, temperature fluctuations correspond to density fluctuations: a region that is hotter than average will also be more dense than average. What COBE effectively saw was a map (blurred by experimental and other errors) of the Universe at an age of 300 000 years, showing a series of very small density fluctuations. We believe that these were subsequently amplified by gravity and eventually led to the structures we can observe today. The question, however, is where did these fluctuations come from? At present there are a few theoretical paradigms (each including a range of particular models) that can explain this—inflation and topological defects—but they both can claim their own successes and shortcomings, so the situation is as yet far from clear. On one hand, the predictions of many inflationary models seem to agree quite well with observations, but none of these successful models is well motivated from a particle-physics point of view. On the other hand, topological-defect models are more deeply rooted within particle physics but their predictions do not seem to compare so well with observations. One should perhaps also point out that this comparison may not be entirely fair: inflationary models are far easier to work with, so the predictions of defect models are not nearly as well known as those of inflationary models: much work remains to be done in this area.

The other unanswered question is, surprisingly enough, the contents of the Universe. Obviously, we can only directly ‘see’ matter that emits light, but it turns out that most of the matter in the Universe actually does not emit light. For example, the visible parts of galaxies are thought to be surrounded by much larger ‘haloes’ of

dark matter, with a size up to 30 times that of the visible part. If all this matter were visible, the night sky would look pretty much like van Gogh's 'Starry night'.

Even though we only have indirect evidence for the existence of this dark matter, we do have a reasonable idea of what it is. About 5% of the matter of the Universe is visible. Another 5% is invisible 'normal matter', that is, baryons (protons and neutrons) and electrons. This is probably in the form of massive compact halo objects, such as brown dwarfs, white dwarfs, planets and possibly black holes. Roughly 25% of the matter of the Universe is thought to be 'cold dark matter' (CDM), that is, heavy non-relativistic exotic particles, such as axions or WIMPS (weakly interacting massive particles). CDM tends to collapse (or 'clump') into the haloes of galaxies, dragging along the dark baryons with it.

Finally, *ca.* 65% of the contents of the Universe is thought to be in the form of a 'cosmological constant', that is, energy of the vacuum: this can also be thought of as cosmic antigravity or the weight of space! Unlike CDM, this never clumps: it tends to make the Universe 'blow up' by making it expand faster and faster. In other words, it forces an accelerated expansion which, according to recent data, has begun very recently. These data have been taken very sceptically by some people. In particular, a period of future acceleration of the Universe, while not posing any problems for cosmologists, would be somewhat problematic for string theory (see § 4) as we know it. However, this is not a basis for judgement: 'data' is not a dirty word, 'assumption' and 'conjecture' are dirty words.

These ingredients are needed for cosmological model building. One starts with a theoretical model, 'adds in' cosmological parameters such as the age, matter contents and so forth and computes its observational consequences. One must then compare notes with observational cosmologists and see whether the model is in agreement with observation: if it does not agree then one had better start again. In the hope of eliminating some of the shortcomings of the Big Bang model, one needs to generalize the model, and yet unexplored extra dimensions are a good place to look for answers.

#### 4. Strings and extra dimensions

It is believed that the unification of the known fundamental interactions of nature requires theories with additional space-time dimensions. Indeed, the only known theory of gravity that is consistent with quantum mechanics is string theory, which is formulated in 10 dimensions (Polchinski 1998).

Even though there are at present no robust ideas about how one can go from these theories to our familiar low-energy space-time cosmology in four dimensions (three spatial dimensions plus time), it is clear that such a process will necessarily involve procedures known as dimensional reduction and compactification. These concepts are mathematically very elaborate, but physically quite simple to understand. Even if the true 'theory of everything' is higher dimensional, one must find how it would manifest itself to observers like us who can only probe four dimensions. Note that this is more general than simply obtaining low-energy or other limits of the theory.

On the other hand, given that we only seem to be able to probe four dimensions, we must figure out why we cannot see the others or, in other words, why (and how) they are hidden. A simple solution is to make these extra dimensions compact and very small. For example, imagine that you are an equilibrist walking along a tightrope

that is suspended high up in the air. For you the tightrope will be essentially one-dimensional. You can safely walk forwards or backwards, but taking a sideways step will have most unpleasant results. On the other hand, for an ant sitting on the same rope, it will be two-dimensional: apart from moving forwards and backwards, it can also safely move around it. It turns out that there are many different ways of performing such compactifications and, even more surprisingly, there are ways to make even infinite dimensions not accessible to us (more on this in §5).

One of the remarkable general consequences of these processes is that the ordinary four-dimensional constants become ‘effective’ quantities, typically being related to the true higher-dimensional fundamental constants through the characteristic length-scales of the extra dimensions. It also happens that these length-scales typically have a non-trivial evolution. In other words, it is extremely difficult and unnatural, within the context of string theory, to make these length-scales constant. Indeed, this is such a pressing question from the string-theory point of view that it has been promoted to the category of a ‘problem’: the so-called ‘radius stabilization problem’ and given that string theorists are (have to be!) extremely optimistic people, the fact that they recognize it as being a problem might well be the best indication that there is something very deep and fundamental about it, even if at this point we cannot quite figure out what it is.

In these circumstances, one is naturally led to the expectation of time and indeed even space variations of the ‘effective’ four-dimensional constants we can measure. In what follows we will go through some of the possible cosmological consequences and observational signatures of these variations, focusing on the fine-structure constant ( $\alpha \equiv e^2/\hbar c$ ), but also discussing other quantities in a less extensive way. Before this, however, we need to make a final excursion into higher-dimensional cosmology.

## 5. A cosmological brane scan

The so-called ‘brane-world scenarios’ are a topic of much recent interest in which variations of four-dimensional constants emerge in a clear and natural way. There is ample evidence that the three forces of particle physics live in  $(3 + 1)$  dimensions: this has been tested on scales from  $10^{-16}$  cm to (for the case of electromagnetism) Solar System scales. However, this may not be the case for gravity. Einstein’s field equations have only been rigorously tested (Will 1993) in the Solar System and the binary pulsar, where the gravitational field exists essentially in empty space (or vacuum). On smaller scales, only tests of linear gravity have been carried out and, even so, only down to scales of *ca.* 0.2 mm (roughly the thickness of a human hair).

Sparkled by the existence, in higher-dimensional theories, of membrane-like objects, the brane-world paradigm arose. It postulates that our Universe is a  $(3 + 1)$  membrane that is somehow embedded in a larger space (commonly called the ‘bulk’), which may or may not be compact and might even have an infinite volume. Particle physics is confined (by some mechanism that need not concern us here) to this brane, while gravity and other hypothetical non-standard-model fields (such as scalar fields) can propagate everywhere. This may also provide a solution to the hierarchy problem, that is, the problem of why gravity is so much weaker than any of the other three forces. The brane-world paradigm’s answer is simply that this is because it has to propagate over a much larger volume.

What are the possible signatures of extra dimensions? In accelerator physics, some possible signatures include missing energy (due to the emission of massive quanta of gravity, gravitons, which escape into the bulk), interference with standard-model processes (new Feynman diagrams with virtual graviton exchange which introduce corrections to measured properties such as cross-sections) or even more exotic phenomena like strong gravity effects (such as black holes).

For gravitation and cosmology, the most characteristic sign would be changes to the gravitational laws, either on very small or very large scales. Indeed, in these models gravity will usually only look four dimensional over a limited range of scales, and below or above this range there should be departures from the four-dimensional behaviour that would be indications of the extra dimensions. The reason why they appear on small enough scales can be understood by recalling the tightrope analogy: only something probing small enough scales (an ant as opposed to the equilibrist) will see the second dimension. The reason why they should appear on a large enough scale is also easy to understand. If you lived in the Cambridgeshire Fens all your life, you could perhaps be forgiven for believing that the Earth is flat and two-dimensional. However, once you travel far enough you will start to see mountains, and once you climb to the top of one you will realize that it is actually curved, and hence it must be curved into something—so there must be some extra dimension for it to curve into.

Other possible clues for brane-type universes and extra dimensions include changes to the Friedman equation (for example, with terms induced by the bulk), the appearance of various large-scale inhomogeneities and variations of the fundamental constants, the main topic of this discussion. Despite this seemingly endless list of possibilities, one should keep in mind that there are strong observational tests and constraints to be faced, some of which we discussed in § 3.

As a good example, there are a number of proposals for brane-world-type models where the acceleration of the Universe is explained by something other than a cosmological constant. Such models will have many of the distinguishing features we have just discussed. A quick search of the literature will reveal about 12 different models. Unfortunately, all the models proposed so far fail for fairly obvious reasons. Since these models will only depart from the standard at very low redshift (usually when acceleration starts), they can fairly easily be made to agree with the CMB. However, the large-scale changes of gravity and (in some cases) the additional energy density components, together with the constraints coming from type-Ia supernovae, will make the models run into trouble when it comes to structure formation: the growth of density fluctuations, lensing and cluster abundances will all go wrong (Avelino & Martins 2002; Uzan & Bernardeau 2001; Aguirre *et al.* 2001; White & Kochanek 2001). Despite this seemingly disappointing start, brane-world scenarios are clearly promising. We simply do not yet have a clear enough understanding of some of their features, the most crucial one probably being the interaction mechanisms between our brane, the bulk and (if they exist) other branes.

## 6. Measuring varying constants: how can we tell?

So we are now almost ready to start looking for varying constants. But how would we recognize a varying constant, if we ever saw one? Two crucial points, which were made implicitly in § 2 but are worth re-emphasizing here, are that one can only measure

dimensionless combinations of dimensional constants and that such measurements are necessarily local.

For example, if I tell you that I am 1.75 m tall, what I am really telling you is that the last time I took the ratio of my height to some other height that I arbitrarily chose to call ‘one metre’, that ratio came out to be 1.75. There is nothing very deep about this number. I would still be the same height if I had decided to tell you my height in feet and inches instead. So far so good. Now, if tomorrow I decide to repeat the above experiment and find a ratio of 1.85, then that could be either because I have grown a bit in the meantime or because I have unknowingly used a smaller ‘metre’, or due to any combination of these two possibilities. The key point is that, even though one of these options might be much more plausible than the others, any of them is a perfectly valid description of what is going on. Moreover, there is no experimental way of verifying one and disproving the others. Similarly, as regards the point on locality, the statement that ‘the speed of light here is the same as the speed of light in Andromeda’ is either a definition or it is completely meaningless, since there is no experimental way of verifying it. These points are crucial and should be clearly understood (Albrecht & Magueijo 1999; Avelino & Martins 1999).

This leads us to an important difference between theory (or model building) and experiment (or observation). From the theory point of view, it is possible, and often very convenient, to build models that have varying dimensional quantities (such as the speed of light, the electron charge or even, if one is brave enough, Planck’s constant). Indeed, such theories became very popular in recent years. However, there is nothing fundamental about such choice, in the sense that any such theory can always be re-cast in a different form, where another constant will be varying instead, but the observational consequences of the two will be exactly identical.

For example, given a theory with a varying constant, say  $c$ , one can always, by a suitable redefinition of units of measurement, transform it into another theory where another constant, say  $e$ , varies. From our discussion in §2, it follows that all we have to do is carry out appropriate redefinitions of our units of length, time and energy. Again, these two theories will be observationally indistinguishable, even though the fundamental equations may look very different in the two cases—and hence one might strongly prefer one of the formulations for reasons of simplicity. On the other hand, the simplest theory having, say, a varying  $c$ , will in general be different from the simplest theory having a varying  $e$  and therefore these two theories can be distinguished experimentally (Magueijo *et al.* 2002).

From the observational point of view, it is meaningless to try to measure variations of dimensional constants per se. When considering observational tests one should focus on dimensionless quantities. The most relevant example is that of the fine-structure constant,  $\alpha \equiv e^2/(\hbar c)$ , which is a measure of the strength of the electromagnetic interactions. Other useful parameters are

$$\beta \equiv \frac{G_{\text{F}} m_{\text{p}}^2 c}{\hbar^3} \quad \text{and} \quad \mu \equiv \frac{m_{\text{p}}}{m_{\text{e}}},$$

where  $G_{\text{F}}$  is Fermi’s constant and  $m_{\text{p}}$  and  $m_{\text{e}}$  are the proton and electron masses, respectively. Having said this, we are now ready to begin the search for variations. As we shall see, the current observational status is rather exciting, but also somewhat confusing.

## 7. Local experiments

Laboratory measurements of the value of the fine-structure constant, and hence limits on its variation, have been carried out for a number of years. The best limit currently available is (Prestage *et al.* 1995)

$$\left| \frac{\dot{\alpha}}{\alpha} \right| < 3.7 \times 10^{-14} \text{ yr}^{-1}. \quad (7.1)$$

This is done by comparing rates between atomic clocks (based on ground-state hyperfine transitions) in alkali atoms with different atomic number  $Z$ . The current best method uses H-maser versus Cs or  $\text{Hg}^+$  clocks, the effect being a relativistic correction of order  $(\alpha Z)^2$ . Future improvements using laser-cooled clocks (Rb or  $\text{Be}^+$ ) may improve this bound by about an order of magnitude. Note that this bound is local, that is, at redshift  $z = 0$ .

On geophysical time-scales, the best constraint (Damour & Dyson 1996) is  $|\dot{\alpha}/\alpha| < 0.7 \times 10^{-16} \text{ yr}^{-1}$ , although there are suggestions that, due to a number of nuclear-physics uncertainties and model dependencies, a more realistic bound might be about an order of magnitude weaker. These come from analysis of Sm-isotope ratios from the natural nuclear reactor at the Oklo (Gabon) uranium mine, on a time-scale of  $1.8 \times 10^9 \text{ yr}$ , corresponding to a cosmological redshift of  $z \sim 0.1$ .

More recently, Fujii *et al.* (2002) carried out an analysis of new samples collected at greater depth in the Oklo mine (hoping to minimize effects of natural contamination). They find two possible ranges of resonance-energy shifts, corresponding to the following values of  $\alpha$ :

$$\frac{\dot{\alpha}}{\alpha} = (0.4 \pm 0.5) \times 10^{-17} \text{ yr}^{-1} \equiv \frac{\Delta\alpha}{\alpha} = -(0.08 \pm 0.10) \times 10^{-7}, \quad (7.2)$$

$$\frac{\dot{\alpha}}{\alpha} = -(4.4 \pm 0.4) \times 10^{-17} \text{ yr}^{-1} \equiv \frac{\Delta\alpha}{\alpha} = (0.88 \pm 0.07) \times 10^{-7}. \quad (7.3)$$

Note that the first value in each line is an average rate of change over the period in question and the second is the overall relative change in the same period. In converting from one to the other, one needs to assume a certain cosmological model—we have assumed the standard one, discussed in §3. Also note that the latter corresponds to a value of  $\alpha$  that was larger in the past, which might be problematic for some models (see the discussion in Martins *et al.* (2002)).

The authors point out that there is plausible but tentative evidence that the second result can be excluded by including a further Gd sample. However, the analysis procedure for Gd data is subject to more uncertainties than the one for Sm, so a more detailed analysis is required before definite conclusions can be drawn.

It should also be noted that most theories predicting variations of fundamental constants can be strongly constrained through gravitational experiments, most notably via tests of the equivalence principle (Will 1993).

## 8. The recent Universe

The standard technique for this type of measurements, which have been attempted since the late 1950s, consists of observing the fine splitting of alkali doublet absorption lines in quasar spectra, and comparing these with standard laboratory spectra. A

different value of  $\alpha$  at early times would mean that electrons would be more loosely (or tightly, depending on the sign of the variation) bound to the nuclei compared with the values for the present day, thus changing the characteristic wavelength of light emitted and absorbed by atoms. This group's best result (Varshalovich *et al.* 2000) using this method is

$$\frac{\Delta\alpha}{\alpha} = (-4.6 \pm 4.3 \pm 1.4) \times 10^{-5}, \quad z \sim 2-4. \quad (8.1)$$

The first error bar corresponds to the statistical (observational) error, while the second is the systematic (laboratory) one. This corresponds to the bound  $|\dot{\alpha}/\alpha| < 1.4 \times 10^{-14} \text{ yr}^{-1}$  over a time-scale of about  $10^{10}$  years. They also obtain constraints on spatial variations (by comparing observations from different regions on the sky),

$$\left| \frac{\Delta\alpha}{\alpha} \right| < 3 \times 10^{-4}, \quad z \sim 2-4. \quad (8.2)$$

Finally, using an analogous technique for  $\text{H}_2$  lines, they can also obtain constraints on the ratio of proton and electron masses,

$$\left| \frac{\Delta\mu}{\mu} \right| < 2 \times 10^{-4}, \quad z \sim 2. \quad (8.3)$$

More recently (Webb *et al.* 2001; Murphy *et al.* 2001), an improved technique has simultaneously used various multiplets from many chemical elements to improve the accuracy by about an order of magnitude. The currently published result is

$$\frac{\Delta\alpha}{\alpha} = (-0.72 \pm 0.18) \times 10^{-5}, \quad z \sim 0.6-3.2, \quad (8.4)$$

corresponding to a four-sigma detection of a *smaller*  $\alpha$  in the past. Further recent data (J. K. Webb 2001, personal communication) strengthen this claim. The analysis of 147 quasar absorption sources (from three independent datasets obtained with the Keck telescope) provide a six-sigma detection,  $\Delta\alpha/\alpha = (-0.60 \pm 0.10) \times 10^{-5}$  in the redshift range  $z \sim 0.6-3.2$ . Furthermore, a large number of tests for systematics has been carried out, and almost all of these are not found to significantly affect the results. The only two exceptions are atmospheric disruption and isotopic ratio shifts, but they act in the 'wrong' way: correcting for these would make the detection stronger (the results presented are uncorrected).

A somewhat different approach consists of using radio and millimetre spectra of quasar absorption lines. Unfortunately, at the moment this can only be used at lower redshifts, yielding the upper limit (Carilli *et al.* 2001)

$$\left| \frac{\Delta\alpha}{\alpha} \right| < 0.85 \times 10^{-5}, \quad z \sim 0.25-0.68. \quad (8.5)$$

Finally, a recent improved technique (Ivanchik *et al.* 2002) of measuring the wavelengths of  $\text{H}_2$  transitions in damped Lyman- $\alpha$  systems observed with the European Space Observatory VLT/UVES telescope (and using the fact that electron vibrational lines depend on the reduced mass of the molecule and this dependence is

different for different transitions) has produced another claimed possible detection

$$\frac{\Delta\mu}{\mu} = (5.7 \pm 3.8) \times 10^{-5}, \quad z \sim 2.4\text{--}3.1, \quad (8.6)$$

$$\frac{\Delta\mu}{\mu} = (12.5 \pm 4.5) \times 10^{-5}, \quad z \sim 2.4\text{--}3.1. \quad (8.7)$$

Here, either value will de-bound depending on which of the two available tables of ‘standard’ laboratory wavelengths one uses. This clearly indicates that systematic effects are not as yet under control in this case.

So a very substantial amount of work has been put into this type of observations. Even if doubts remain about systematics, a six-sigma detection is a quite strong result and should be taken seriously. (As a comparison, the result is roughly as strong as the detection, using type-Ia supernovae data, of a non-zero value of the cosmological constant.) Now, if these variations existed at relatively recent times in the history of the Universe, one is naturally led to the question of what was happening at earlier times—presumably the variations relative to the present-day values would have been stronger then.

## 9. The early Universe: BBN and CMB

At much higher redshifts, two of the pillars of standard cosmology (discussed in §3) offer very exciting prospects for studies of variations of constants. Firstly, BBN has the obvious advantage of probing the highest redshifts ( $z \sim 10^{10}$ ), but it has a strong drawback in that one is always forced to make an assumption on how the neutron-to-proton mass difference depends on  $\alpha$ . No known particle-physics model provides such a relation, so one usually has to resort to the phenomenological expression by Gasser & Leutwyler (1982),  $\Delta m = 2.05 - 0.76(1 + \Delta\alpha/\alpha)$ . This is needed to estimate the effect of a varying  $\alpha$  on the  ${}^4\text{He}$  abundance. The abundances of the other light elements depend much less strongly on this assumption but, on the other hand, these abundances are much less well known observationally.

The CMB probes intermediate redshifts, and has the significant advantage that one has (or will soon have) highly accurate data. A varying fine-structure constant changes the ionization history of the Universe: it changes the Thomson scattering cross-section for all interacting species and also changes the recombination history of hydrogen (by far the dominant contribution) and other species through changes in the energy levels and binding energies. This will obviously have important effects on the CMB’s angular power spectrum, which has now been measured by a number of experiments. Suppose that  $\alpha$  was larger at the epoch of recombination. The position of the first Doppler peak would then move smaller angular scales, its amplitude would increase due to a larger early integrated Sachs–Wolfe effect and the damping at small angular scales would decrease.

Furthermore, a varying  $\alpha$  also has an effect on the large-scale structure (LSS) power spectrum, since it changes the horizon size and hence the turnover scale in the matter power spectrum. It should be noted that, although the CMB and LSS are in some sense complementary, they cannot be blindly combined together, since they are sensitive to different cosmological epochs at which  $\alpha$  could have different values. Therefore, the optimal strategy is to use LSS information to provide priors

(in a self-consistent way) for other cosmological parameters which we can reliably assume to be unchanged throughout the cosmological epochs in question.

We have recently carried out detailed analyses of the effects of a varying  $\alpha$  on BBN, the CMB and LSS and compared the results with the latest available observational results in each case (Avelino *et al.* 2001; Martins *et al.* 2002). We find that, although the current data have a very slight preference for a smaller value of  $\alpha$  in the past, they are consistent with no variation and, furthermore, restrict any such variation, from the epoch of recombination to the present day, to less than *ca.* 4%.

The effects of varying constants are somewhat degenerate with other cosmological parameters, like the baryon density, Hubble parameter or re-ionization. In particular, the effect of the baryon density seems crucial. For the values quoted above, the baryon density of the Universe agrees with the standard result (Burles *et al.* 2001). However, there have been recent claims (Coc *et al.* 2002) that the use of improved BBN calculations and observations may lead to a lower value of the baryon density. If one assumes this lower value instead, our estimations for  $\alpha$  would become a detection at more than two sigma.

At a practical level, one needs to find ways of getting around these degeneracies. Three approaches are being actively tried by ourselves and other groups. The first (obvious) one is to use better data—future CMB satellite experiments such as Microwave Anisotropy Probe and Planck Surveyor should considerably improve the above results, and this has been recently studied in detail (Martins *et al.* 2002). The second approach is to use additional microwave background information (such as polarization, when data become available) and the final one is to exploit the complementarity of various datasets (as hinted above). While at the moment the constraints on  $\alpha$  coming from BBN and CMB data allow variation from the present-day value by *ca.* 4%, there is a good chance that progress in both the theoretical understanding and the quality of the available data will allow us to determine the value of  $\alpha$  from the CMB with much better than *ca.* 1% accuracy within this decade.

## 10. So what is your point?

We have seen that constraints on variations of fundamental constants in recent times are fairly strong and any drastic recent departures from the standard scenario are excluded. On the other hand, there are no significant constraints in the pre-nucleosynthesis era, which leaves a rather large open space for theorists to build models. In between, there are various detections claimed, particularly from quasar absorption sources at redshifts of *ca.* 3. These should definitely be taken seriously, although the situation is far from settled. The jury is still out on the case of the existence of extra dimensions: there is as yet no unambiguous observational proof (a ‘smoking gun’ has not been found), but considerable supporting evidence is accumulating.

Apart from more observational work, there are deep theoretical issues to be clarified. The question as to whether all dimensionless parameters in the final physical ‘theory of everything’ will be fixed by consistency conditions or if certain of them will remain arbitrary is today a question of belief—it does not have a scientific answer at present. By ‘arbitrary’ I mean in this context that a given dimensionless parameter assumed its value in the process of the cosmological evolution of the Universe at an

early stage. Hence, with a greater or lesser probability, it could also have assumed other values and it could possibly also change in the course of this evolution.

Physics is a logical activity, and hence (unlike other intellectual pursuits) frowns on radical departures. Physicists much prefer to proceed by reinterpretation, whereby elegant new ideas provide a sounder basis for what one already knows, while also leading to further, novel results with at least a prospect of testability. However, it is often not easy to see how old concepts fit into a new framework. How would our views of the world be changed if decisive evidence is eventually found for extra dimensions and varying fundamental constants?

Theories obeying the Einstein and strong-equivalence principles are metric theories of gravity (Will 1993). In such theories the space-time is endowed with a symmetric metric, freely falling bodies follow geodesics of this metric and in local freely falling frames the non-gravitational physics laws are written in the language of special relativity. If the Einstein equivalence principle holds, the effects of gravity are equivalent to the effects of living in a curved space-time. The strong-equivalence principle contains the Einstein equivalence principle as the special case where local gravitational forces (such as Cavendish experiments or gravimeter measurements, for example) are ignored. If the strong-equivalence principle is strictly valid, there should be one and only one gravitational field in the Universe, namely the metric.

Varying non-gravitational constants are forbidden by general relativity and (in general) all metric theories. A varying fine-structure constant will violate the equivalence principle, thus signalling the breakdown of (four-dimensional) gravitation as a geometric phenomenon. It will also reveal the existence of further (as yet undiscovered) gravitational fields in the Universe and may be a very strong proof for the existence of additional space-time dimensions. As such, it will be nothing short of a revolution—even more drastic than the one where Newtonian gravity became part of Einsteinian gravity. Also, while not telling us, by itself, too much about the ‘theory of everything’, it will provide some strong clues about what to look for and where to look for it.

Most people (scientists and non-scientists alike) normally make a distinction between physics (studying down-to-earth things) and astronomy (studying the heavens above). This distinction is deeply rooted in pre-historic times and is still clearly visible today. Indeed, in my own area of research, such distinction only started to blur some 30 or so years ago, when a few cosmologists noted that the early Universe should have been through a series of phase transitions, about which particle physicists knew a fair amount, and hence it would be advisable for cosmologists to start learning particle physics. Nowadays, the circle is closing, with particle physicists finally beginning to realize that, as they try to probe earlier and earlier epochs where physical conditions are more and more extreme, there is no laboratory on Earth capable of reproducing these such conditions. Indeed, the only laboratory that is fit for the job is the early Universe itself. Hence, it is also advisable for particle physicists to learn cosmology.

The topic of extra dimensions and varying fundamental constants is, to my mind, the perfect example of a problem at the borderline between the two areas, where knowledge of only one of the sides, no matter how deep, is a severe handicap. This obviously makes it a difficult topic, but also an extremely exciting one, to work on.

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