

# INCONSTANT

HOW UNIMAGINABLY STRANGE the world would be if the constants of nature had different values. The so-called fine-structure constant ( $\alpha$ ), for example, is about  $1/137$ . Were it another value, matter and energy would interact in bizarre ways; indeed, the very distinction between matter and energy could melt away.

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By John D. Barrow and John K. Webb

Some things never change. Physicists call them the constants of nature. Such quantities as the velocity of light,  $c$ , Newton's constant of gravitation,  $G$ , and the mass of the electron,  $m_e$ , are assumed to be the same at all places and times in the universe. They form the scaffolding around which the theories of physics are erected, and they define the fabric of our universe. Physics has progressed by making ever more accurate measurements of their values.

And yet, remarkably, no one has ever successfully predicted or explained any of the constants. Physicists have no idea why they take the special numerical values that they do. In SI units,  $c$  is 299,792,458;  $G$  is  $6.673 \times 10^{-11}$ ; and  $m_e$  is  $9.10938188 \times 10^{-31}$ —numbers that follow no discernible pattern. The only thread running through the values is that if many of them were even slightly different, complex atomic structures such as living beings would not be possible. The desire to explain the constants has been one of the driving forces behind efforts to develop a complete unified description of nature, or “theory of everything.” Physicists have hoped that such a theory would show that each of the constants of nature could have only one logically possible value. It would reveal an underlying order to the seeming arbitrariness of nature.

In recent years, however, the status of the constants has grown more muddled, not less. Researchers have found that the best candidate for a theory of everything, the variant of string theory called M-theory, is self-consistent only if the universe has more than four dimensions of space and time—as many as seven more. One implication is that the constants we observe may not, in fact, be the truly fundamental ones. Those live in the full higher-dimensional space, and we see only their three-dimensional “shadows.”

Meanwhile physicists have also come to appreciate that the values of many of the constants may be the result of

*Do the  
inner workings  
of nature  
change with time?*

# CONSTANTS

mere happenstance, acquired during random events and elementary particle processes early in the history of the universe. In fact, string theory allows for a vast number— $10^{500}$ —of possible “worlds” with different self-consistent sets of laws and constants [see “The String Theory Landscape,” by Raphael Bousso and Joseph Polchinski; *SCIENTIFIC AMERICAN*, September 2004]. So far researchers have no idea why our combination was selected. Continued study may reduce the number of logically possible worlds to one, but we have to remain open to the unnerving possibility that our known universe is but one of many—a part of a multiverse—and that different parts of the multiverse exhibit different solutions to the theory, our observed laws of nature being merely one edition of many systems of local bylaws [see “Parallel Universes,” by Max Tegmark; *SCIENTIFIC AMERICAN*, May 2003].

No further explanation would then be possible for many of our numerical constants other than that they constitute a rare combination that permits consciousness to evolve. Our observable universe could be one of many isolated oases surrounded by an infinity of lifeless space—a surreal place where different forces of nature hold sway and particles such as electrons or structures such as carbon atoms and DNA molecules could be impossibilities. If you tried to venture into that outside world, you would cease to be.

Thus, string theory gives with the right hand and takes with the left. It was

devised in part to explain the seemingly arbitrary values of the physical constants, and the basic equations of the theory contain few arbitrary parameters. Yet so far string theory offers no explanation for the observed values of the constants.

### A Ruler You Can Trust

INDEED, THE WORD “constant” may be a misnomer. Our constants could vary both in time and in space. If the extra dimensions of space were to change in size, the “constants” in our three-dimensional world would change with them. And if we looked far enough out in space, we might begin to see regions where the “constants” have settled into different values. Ever since the 1930s, researchers have speculated that the constants may not be constant. String theory gives this idea a theoretical plausibility and makes it all the more important for observers to search for deviations from constancy.

Such experiments are challenging. The first problem is that the laboratory apparatus itself may be sensitive to changes in the constants. The size of all atoms could be increasing, but if the ruler you are using to measure them is getting longer, too, you would never be able to tell. Experimenters routinely assume that their reference standards—rulers, masses, clocks—are fixed, but they cannot do so when testing the constants. They must focus their attention on constants that have no units—they are pure numbers—so that their values are the same irrespective of the units system. An

example is the ratio of two masses, such as the proton mass to the electron mass.

One ratio of particular interest combines the velocity of light,  $c$ , the electric charge on a single electron,  $e$ , Planck’s constant,  $h$ , and the so-called vacuum permittivity,  $\epsilon_0$ . This famous quantity,  $\alpha = e^2/2\epsilon_0hc$ , called the fine-structure constant, was first introduced in 1916 by Arnold Sommerfeld, a pioneer in applying the theory of quantum mechanics to electromagnetism. It quantifies the relativistic ( $c$ ) and quantum ( $h$ ) qualities of electromagnetic ( $e$ ) interactions involving charged particles in empty space ( $\epsilon_0$ ). Measured to be equal to  $1/137.03599976$ , or approximately  $1/137$ ,  $\alpha$  has endowed the number 137 with a legendary status among physicists (it usually opens the combination locks on their briefcases).

If  $\alpha$  had a different value, all sorts of vital features of the world around us would change. If the value were lower, the density of solid atomic matter would fall (in proportion to  $\alpha^3$ ), molecular bonds would break at lower temperatures ( $\alpha^2$ ), and the number of stable elements in the periodic table could increase ( $1/\alpha$ ). If  $\alpha$  were too big, small atomic nuclei could not exist, because the electrical repulsion of their protons would overwhelm the strong nuclear force binding them together. A value as big as 0.1 would blow apart carbon.

The nuclear reactions in stars are especially sensitive to  $\alpha$ . For fusion to occur, a star’s gravity must produce temperatures high enough to force nuclei together despite their tendency to repel one another. If  $\alpha$  exceeded 0.1, fusion would be impossible (unless other parameters, such as the electron-to-proton mass ratio, were adjusted to compensate). A shift of just 4 percent in  $\alpha$  would alter the energy levels in the nucleus of carbon to such an extent that the production of this element by stars would shut down.

### Nuclear Proliferation

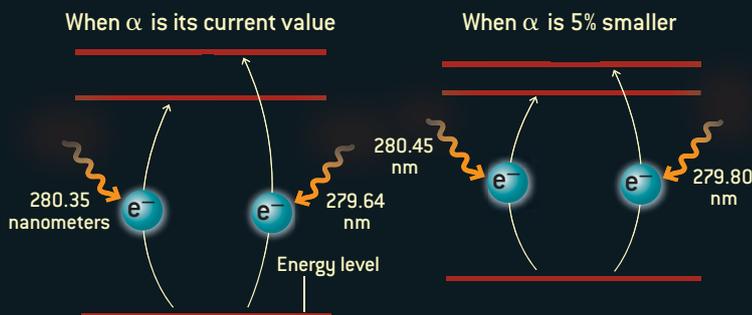
THE SECOND experimental problem, less easily solved, is that measuring changes in the constants requires high-precision equipment that remains stable long enough to register any changes.

## Overview/Constants of Physics

- The equations of physics are filled with quantities such as the speed of light. Physicists routinely assume that these quantities are constant: they have the same values everywhere in space and time.
- Over the past six years, the authors and their collaborators have called that assumption into question. By comparing quasar observations with laboratory reference measurements, they have argued that chemical elements in the distant past absorbed light differently than the same elements do today. The difference can be explained by a change in one of the constants, known as the fine-structure constant, of a few parts per million.
- Small though it might seem, this change, if confirmed, would be revolutionary. It would mean that the observed constants are not universal and could be a sign that space has extra dimensions.

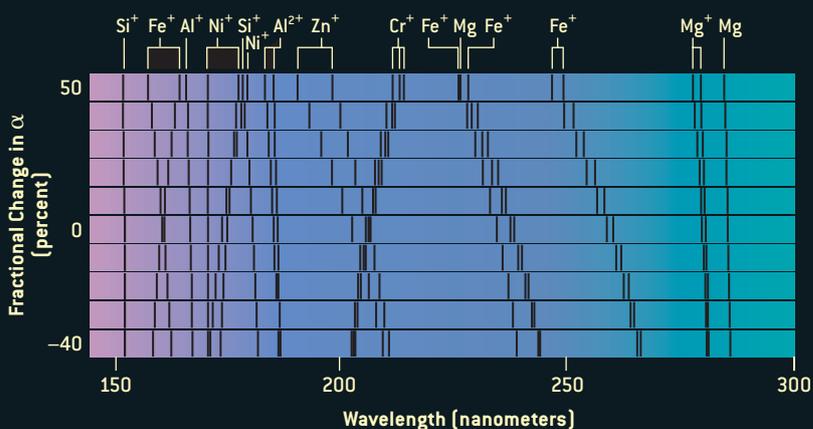
# LIGHT AND THE FINE-STRUCTURE CONSTANT

Several of the best-known constants of nature, including the speed of light, can be combined into the fine-structure constant ( $\alpha$ )—a number that represents how strongly particles interact through electromagnetic forces. One such interaction is the absorption of photons by atoms. Illuminated by light, an atom absorbs specific colors, each corresponding to photons of a certain wavelength.



**ENERGY LEVELS** of electrons within the atom describe the absorption process. The energy of a photon is transferred to an electron, which jumps up the ladder of allowable levels. Each possible jump corresponds to a distinct wavelength. The spacing of levels depends on how strongly the electron is attracted to the atomic nucleus and therefore on  $\alpha$ . In the case of magnesium ions ( $\text{Mg}^+$ ), if  $\alpha$  were smaller, the levels would be closer together. Photons would need less energy (meaning a longer wavelength) to kick electrons up the ladder.

**SIMULATED SPECTRA** show how changing  $\alpha$  affects the absorption of near-ultraviolet light by various atomic species. The horizontal black lines represent absorbed wavelengths. Each type of atom or ion has a unique pattern of lines. Changes in the fine-structure constant affect magnesium ( $\text{Mg}$ ), silicon ( $\text{Si}$ ) and aluminum ( $\text{Al}$ ) less than iron ( $\text{Fe}$ ), zinc ( $\text{Zn}$ ), chromium ( $\text{Cr}$ ) and nickel ( $\text{Ni}$ ).



Even atomic clocks can detect drifts in the fine-structure constant only over days or, at most, years. If  $\alpha$  changed by more than four parts in  $10^{15}$  over a three-year period, the best clocks would see it. None have. That may sound like an impressive confirmation of constancy, but three years is a cosmic eyeblink. Slow but substantial changes during the long history of the universe would have gone unnoticed.

Fortunately, physicists have found other tests. During the 1970s, scientists from the French atomic energy commission noticed something peculiar about the isotopic composition of ore from a uranium mine at Oklo in Gabon, West Africa: it looked like the waste products of a nuclear reactor. About two billion years ago, Oklo must have been the site

of a natural reactor [see “A Natural Fission Reactor,” by George A. Cowan; *SCIENTIFIC AMERICAN*, July 1976].

In 1976 Alexander Shlyakhter of the Nuclear Physics Institute in St. Petersburg, Russia, noticed that the ability of a natural reactor to function depends crucially on the precise energy of a particular state of the samarium nucleus that facilitates the capture of neutrons. And that energy depends sensitively on the value of  $\alpha$ . So if the fine-structure constant had been slightly different, no chain reaction could have occurred. But one did occur, which implies that the constant has not changed by more than one part in  $10^8$  over the past two billion years. (Physicists continue to debate the exact quantitative results because of the inevitable uncertainties about the

conditions inside the natural reactor.)

In 1962 P. James E. Peebles and Robert Dicke of Princeton University first applied similar principles to meteorites: the abundance ratios arising from the radioactive decay of different isotopes in these ancient rocks depend on  $\alpha$ . The most sensitive constraint involves the beta decay of rhenium into osmium. According to recent work by Keith Olive of the University of Minnesota, Maxim Pospelov of the University of Victoria in British Columbia and their colleagues, at the time the rocks formed,  $\alpha$  was within two parts in  $10^6$  of its current value. This result is less precise than the Oklo data but goes back further in time, to the origin of the solar system 4.6 billion years ago.

To probe possible changes over even longer time spans, researchers must look

# LOOKING FOR CHANGES IN QUASAR LIGHT

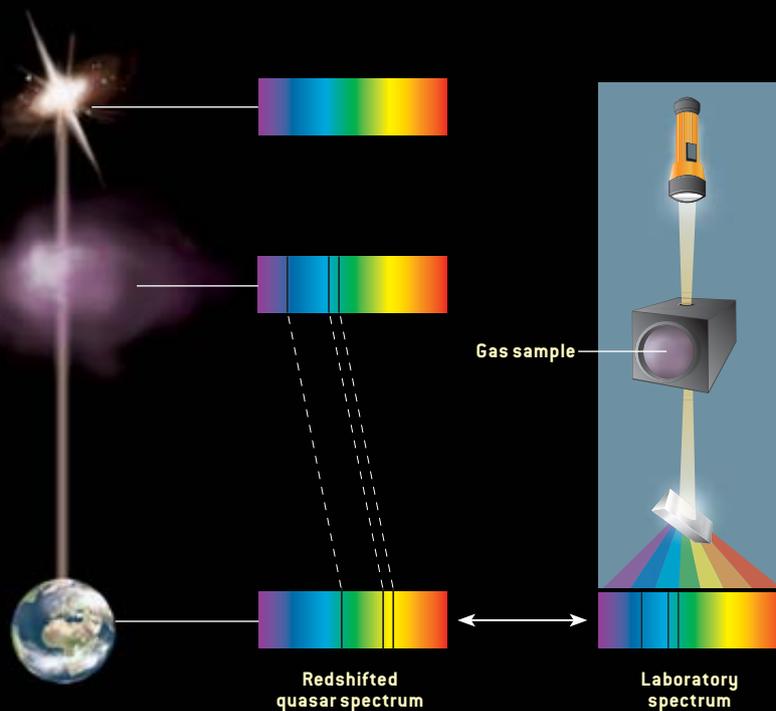
A distant gas cloud, backlit by a quasar, gives astronomers an opportunity to probe the process of light absorption—and therefore the value of the fine-structure constant—earlier in cosmic history.

**1** Light from a quasar begins its journey to Earth billions of years ago with a smooth spectrum

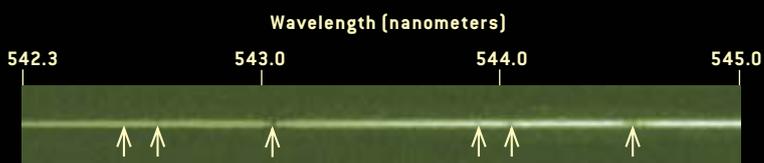
**2** On its way, the light passes through one or more gas clouds. The gas blocks specific wavelengths, creating a series of black lines in the spectrum. For studies of the fine-structure constant, astronomers focus on absorption by metals

**3** By the time the light arrives on Earth, the wavelengths of the lines have been shifted by cosmic expansion. The amount of shift indicates the distance of the cloud and, hence, its age

**4** The spacing of the spectral lines can be compared with values measured in the laboratory. A discrepancy suggests that the fine-structure constant used to have a different value



**QUASAR SPECTRUM**, taken at the European Southern Observatory's Very Large Telescope, shows absorption lines produced by gas clouds between the quasar (arrowed at right) and us. The position of the lines (arrowed at far right) indicates that the light passed through the clouds about 7.5 billion years ago.



to the heavens. Light takes billions of years to reach our telescopes from distant astronomical sources. It carries a snapshot of the laws and constants of physics at the time when it started its journey or encountered material en route.

## Line Editing

ASTRONOMY FIRST entered the constants story soon after the discovery of quasars in 1965. The idea was simple. Quasars had just been discovered and identified as bright sources of light located at huge distances from Earth. Because the path of light from a quasar to us is so long, it inevitably intersects the gaseous outskirts of young galaxies. That gas absorbs the quasar light at particular frequencies, imprinting a bar code of narrow lines onto the quasar spectrum [see box above].

Whenever gas absorbs light, electrons within the atoms jump from a low energy state to a higher one. These energy levels are determined by how tightly the atomic nucleus holds the electrons, which depends on the strength of the electromagnetic force between them—and therefore on the fine-structure constant. If the constant was different at the time when the light was absorbed or in the particular region of the universe where it happened, then the energy required to lift the electron would differ from that required today in laboratory experiments, and the wavelengths of the transitions seen in the spectra would differ. The way in which the wavelengths change depends critically on the orbital configuration of the electrons. For a given change in  $\alpha$ , some wavelengths shrink, whereas others increase. The complex

pattern of effects is hard to mimic by data calibration errors, which makes the test astonishingly powerful.

Before we began our work seven years ago, attempts to perform the measurement had suffered from two limitations. First, laboratory researchers had not measured the wavelengths of many of the relevant spectral lines with sufficient precision. Ironically, scientists used to know more about the spectra of quasars billions of light-years away than about the spectra of samples here on Earth. We needed high-precision laboratory measurements against which to compare the quasar spectra, so we persuaded experimenters to undertake them. Initial measurements were done by Anne Thorne and Juliet Pickering of Imperial College London, followed by groups led by Sveneric Johansson of

Lund Observatory in Sweden and Ulf Griesmann and Rainer Kling of the National Institute of Standards and Technology in Maryland.

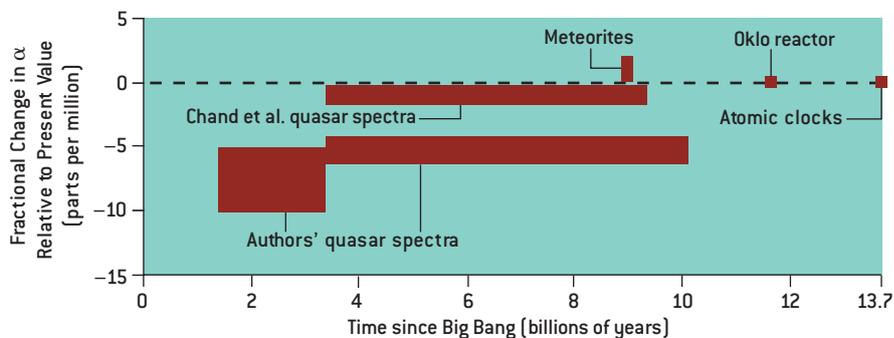
The second problem was that previous observers had used so-called alkali-doublet absorption lines—pairs of absorption lines arising from the same gas, such as carbon or silicon. They compared the spacing between these lines in quasar spectra with laboratory measurements. This method, however, failed to take advantage of one particular phenomenon: a change in  $\alpha$  shifts not just the spacing of atomic energy levels relative to the lowest-energy level, or ground state, but also the position of the ground state itself. In fact, this second effect is even stronger than the first. Consequently, the highest precision observers achieved was only about one part in  $10^4$ .

In 1999 one of us (Webb) and Victor V. Flambaum of the University of New South Wales in Australia came up with a method to take both effects into account. The result was a breakthrough: it meant 10 times higher sensitivity. Moreover, the method allows different species (for instance, magnesium and iron) to be compared, which allows additional cross-checks. Putting this idea into practice took complicated numerical calculations to establish exactly how the observed wavelengths depend on  $\alpha$  in all different atom types. Combined with modern telescopes and detectors, the new approach, known as the many-multiplet method, has enabled us to test the constancy of  $\alpha$  with unprecedented precision.

## Changing Minds

WHEN EMBARKING ON this project, we anticipated establishing that the value of the fine-structure constant long ago was the same as it is today; our contribution would simply be higher precision. To our surprise, the first results, in 1999, showed small but statistically significant differences. Further data confirmed this finding. Based on a total of 128 quasar absorption lines, we found an average increase in  $\alpha$  of close to six parts in a million over the past six billion to 12 billion years.

Extraordinary claims require ex-



MEASUREMENTS of the fine-structure constant are inconclusive. Some indicate that the constant used to be smaller, and some do not. Perhaps the constant varied earlier in cosmic history and no longer does so. (The boxes represent a range of data.)

traordinary evidence, so our immediate thoughts turned to potential problems with the data or the analysis methods. These uncertainties can be classified into two types: systematic and random. Random uncertainties are easier to understand; they are just that—random. They differ for each individual measurement but average out to be close to zero over a large sample. Systematic uncertainties, which do not average out, are harder to deal with. They are endemic in astronomy. Laboratory experimenters can alter their instrumental setup to minimize them, but astronomers cannot change the universe, and so they are forced to accept that all their methods of gathering data have an irremovable bias. For example, any survey of galaxies will tend to be overrepresented by bright galaxies because they are easier to see. Identifying and neutralizing these biases is a constant challenge.

The first one we looked for was a distortion of the wavelength scale against which the quasar spectral lines were measured. Such a distortion might conceivably be introduced, for example,

during the processing of the quasar data from their raw form at the telescope into a calibrated spectrum. Although a simple linear stretching or compression of the wavelength scale could not precisely mimic a change in  $\alpha$ , even an imprecise mimicry might be enough to explain our results. To test for problems of this kind, we substituted calibration data for the quasar data and analyzed them, pretending they were quasar data. This experiment ruled out simple distortion errors with high confidence.

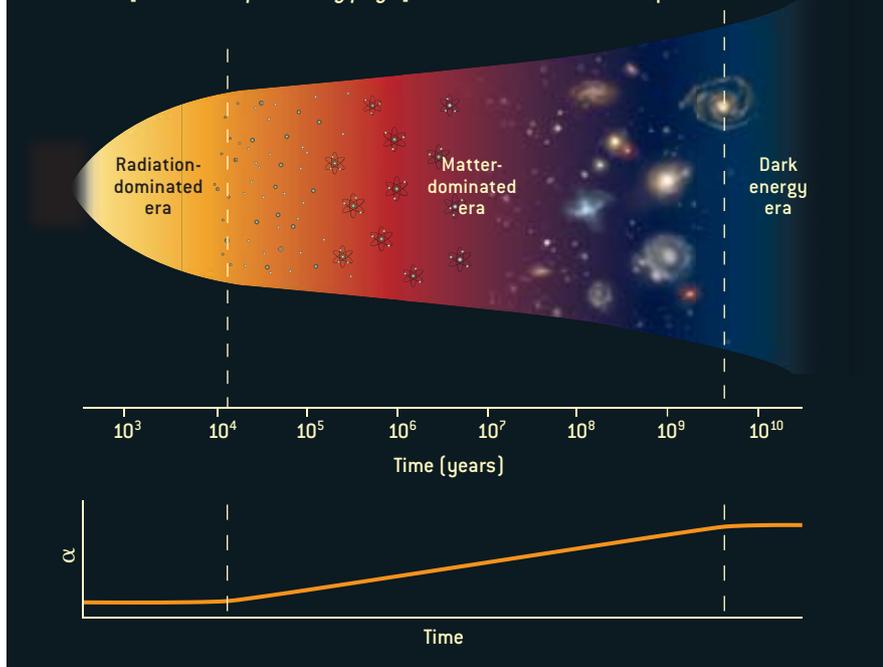
For more than two years, we put up one potential bias after another, only to rule it out after detailed investigation as too small an effect. So far we have identified just one potentially serious source of bias. It concerns the absorption lines produced by the element magnesium. Each of the three stable isotopes of magnesium absorbs light of a different wavelength, but the three wavelengths are very close to one another, and quasar spectroscopy generally sees the three lines blended as one. Based on laboratory measurements of the relative abundances of the three isotopes, researchers infer

### THE AUTHORS

JOHN D. BARROW and JOHN K. WEBB began to work together to probe the constants of nature in 1996, when Webb spent a sabbatical with Barrow at the University of Sussex in England. Barrow had been exploring new theoretical possibilities for varying constants, and Webb was immersed in quasar observations. Their project soon drew in other physicists and astronomers, notably Victor V. Flambaum of the University of New South Wales in Australia, Michael T. Murphy of the University of Cambridge and João Magueijo of Imperial College London. Barrow is now a professor at Cambridge and a Fellow of the Royal Society, and Webb is a professor at New South Wales. Both are known for their efforts to explain science to the public. Barrow has written 17 nontechnical books; his play, *Infinites*, has been staged in Italy; and he has spoken in venues as diverse as the Venice Film Festival, 10 Downing Street and the Vatican. Webb regularly lectures internationally and has worked on more than a dozen TV and radio programs.

## SOMETIMES IT CHANGES, SOMETIMES NOT

According to the authors' theory, the fine-structure constant should have stayed constant during certain periods of cosmic history and increased during others. The data [see box on preceding page] are consistent with this prediction.



the contribution of each. If these abundances in the young universe differed substantially—as might have happened if the stars that spilled magnesium into their galaxies were, on average, heavier than their counterparts today—those differences could simulate a change in  $\alpha$ .

But a study published this year indicates that the results cannot be so easily explained away. Yeshe Fenner and Brad K. Gibson of Swinburne University of Technology in Australia and Michael T. Murphy of the University of Cambridge found that matching the isotopic abundances to emulate a variation in  $\alpha$  also results in the overproduction of nitrogen in the early universe—in direct conflict with observations. If so, we must confront the likelihood that  $\alpha$  really has been changing.

The scientific community quickly realized the immense potential significance of our results. Quasar spectroscopists around the world were hot on the trail and rapidly produced their own measurements. In 2003 teams led by Sergei Levshakov of the Ioffe Physico-Technical Institute in St. Petersburg, Russia, and Ralf Quast of the University of Hamburg

in Germany investigated three new quasar systems. Last year Hum Chand and Raghunathan Srikanth of the Inter-University Center for Astronomy and Astrophysics in India, Patrick Petitjean of the Institute of Astrophysics and Bastien Aracil of LERMA in Paris analyzed 23 more. None of these groups saw a change in  $\alpha$ . Chand argued that any change must be less than one part in  $10^6$  over the past six billion to 10 billion years.

How could a fairly similar analysis, just using different data, produce such a radical discrepancy? As yet the answer is unknown. The data from these groups are of excellent quality, but their samples are substantially smaller than ours and do not go as far back in time. The Chand analysis did not fully assess all the experimental and systematic errors—and, being based on a simplified version of the many-multiplet method, might have introduced new ones of its own.

One prominent astrophysicist, John Bahcall of Princeton, has criticized the many-multiplet method itself, but the problems he has identified fall into the category of random uncertainties, which should wash out in a large sample. He

and his colleagues, as well as a team led by Jeffrey Newman of Lawrence Berkeley National Laboratory, have looked at emission lines rather than absorption lines. So far this approach is much less precise, but in the future it may yield useful constraints.

### Reforming the Laws

IF OUR FINDINGS prove to be right, the consequences are enormous, though only partially explored. Until quite recently, all attempts to evaluate what happens to the universe if the fine-structure constant changes were unsatisfactory. They amounted to nothing more than assuming that  $\alpha$  became a variable in the same formulas that had been derived assuming it is a constant. This is a dubious practice. If  $\alpha$  varies, then its effects must conserve energy and momentum, and they must influence the gravitational field in the universe. In 1982 Jacob D. Bekenstein of the Hebrew University of Jerusalem was the first to generalize the laws of electromagnetism to handle inconstant constants rigorously. The theory elevates  $\alpha$  from a mere number to a so-called scalar field, a dynamic ingredient of nature. His theory did not include gravity, however. Four years ago one of us (Barrow), with Håvard Sandvik and João Magueijo of Imperial College London, extended it to do so.

This theory makes appealingly simple predictions. Variations in  $\alpha$  of a few parts per million should have a completely negligible effect on the expansion of the universe. That is because electromagnetism is much weaker than gravity on cosmic scales. But although changes in the fine-structure constant do not affect the expansion of the universe significantly, the expansion affects  $\alpha$ . Changes to  $\alpha$  are driven by imbalances between the electric field energy and magnetic field energy. During the first tens of thousands of years of cosmic history, radiation dominated over charged particles and kept the electric and magnetic fields in balance. As the universe expanded, radiation thinned out, and matter became the dominant constituent of the cosmos. The electric and magnetic energies became unequal,

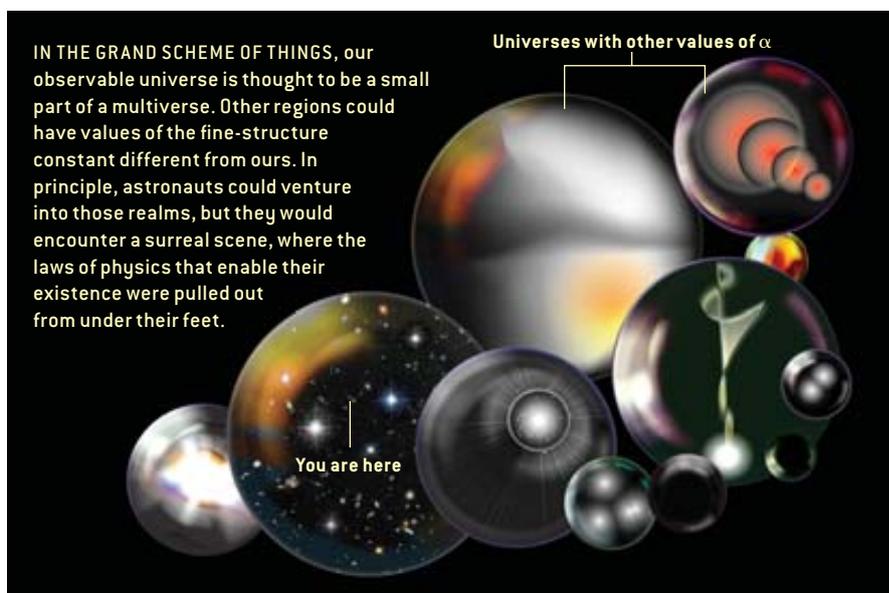
and  $\alpha$  started to increase very slowly, growing as the logarithm of time. About six billion years ago dark energy took over and accelerated the expansion, making it difficult for all physical influences to propagate through space. So  $\alpha$  became nearly constant again.

This predicted pattern is consistent with our observations. The quasar spectral lines represent the matter-dominated period of cosmic history, when  $\alpha$  was increasing. The laboratory and Oklo results fall in the dark-energy-dominated period, during which  $\alpha$  has been constant. The continued study of the effect of changing  $\alpha$  on radioactive elements in meteorites is particularly interesting, because it probes the transition between these two periods.

## Alpha Is Just the Beginning

ANY THEORY worthy of consideration does not merely reproduce observations; it must make novel predictions. The above theory suggests that varying the fine-structure constant makes objects fall differently. Galileo predicted that bodies in a vacuum fall at the same rate no matter what they are made of—an idea known as the weak equivalence principle, famously demonstrated when Apollo 15 astronaut David Scott dropped a feather and a hammer and saw them hit the lunar dirt at the same time. But if  $\alpha$  varies, that principle no longer holds exactly. The variations generate a force on all charged particles. The more protons an atom has in its nucleus, the more strongly it will feel this force. If our quasar observations are correct, then the accelerations of different materials differ by about one part in  $10^{14}$ —too small to see in the laboratory by a factor of about 100 but large enough to show up in planned missions such as STEP (space-based test of the equivalence principle).

There is a last twist to the story. Previous studies of  $\alpha$  neglected to include one vital consideration: the lumpiness of the universe. Like all galaxies, our Milky Way is about a million times denser than the cosmic average, so it is not expanding along with the universe. In 2003 Barrow and David F. Mota of Cambridge calculated that  $\alpha$  may behave dif-



ferently within the galaxy than inside emptier regions of space. Once a young galaxy condenses and relaxes into gravitational equilibrium,  $\alpha$  nearly stops changing inside it but keeps on changing outside. Thus, the terrestrial experiments that probe the constancy of  $\alpha$  suffer from a selection bias. We need to study this effect more to see how it would affect the tests of the weak equivalence principle. No spatial variations of  $\alpha$  have yet been seen. Based on the uniformity of the cosmic microwave background radiation, Barrow recently showed that  $\alpha$  does not vary by more than one part in  $10^8$  between regions separated by 10 degrees on the sky.

So where does this flurry of activity leave science as far as  $\alpha$  is concerned? We await new data and new analyses to confirm or disprove that  $\alpha$  varies at the level claimed. Researchers focus on  $\alpha$ , over

the other constants of nature, simply because its effects are more readily seen. If  $\alpha$  is susceptible to change, however, other constants should vary as well, making the inner workings of nature more fickle than scientists ever suspected.

The constants are a tantalizing mystery. Every equation of physics is filled with them, and they seem so prosaic that people tend to forget how unaccountable their values are. Their origin is bound up with some of the grandest questions of modern science, from the unification of physics to the expansion of the universe. They may be the superficial shadow of a structure larger and more complex than the three-dimensional universe we witness around us. Determining whether constants are truly constant is only the first step on a path that leads to a deeper and wider appreciation of that ultimate vista. SA

### MORE TO EXPLORE

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**A Simple Cosmology with a Varying Fine Structure Constant.** H. B. Sandvik, J. D. Barrow and J. Magueijo in *Physical Review Letters*, Vol. 88, Paper No. 031302; January 2, 2002. [astro-ph/0107512](http://arxiv.org/abs/astro-ph/0107512)

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