Astronomical Constraints on the Cosmic Evolution of the Fine Structure Constant and Possible Quantum Dimensions

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We present measurements of absorption by the 21 cm hyperfine transition of neutral hydrogen toward radio sources at substantial look-back times. These data are used in combination with observations of rotational transitions of common interstellar molecules to set limits on the evolution of the fine structure constant: $\frac{\dot{\alpha}}{\alpha} < 3.5 \times 10^{-15}$ yr^{-1}, to a look-back time of 4.8 Gyr. In the context of string theory, the limit on the secular evolution of the scale factor of the compact dimensions, R, is $\frac{\dot{R}}{R} < 10^{-15}$ yr^{-1}. Including terrestrial and other astronomical measurements places 2σ limits on slow oscillations of R from the present to the epoch of cosmic nucleosynthesis, just seconds after the big bang, of $\frac{\Delta R}{R} < 10^{-5}$.

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Since the startling realization that we live in an evolving universe, there have been numerous hypotheses concerning the cosmic evolution of physical constants. Dirac [1] pointed out that the ratio between the strength of the gravitational force to that of the electromagnetic force $\approx 10^{39} \approx$ the age of the universe measured in atomic units of time. He speculated that such large dimensionless numbers may be more fundamental than the supposed fundamental constants, and that the constants evolve in such a way that observers at any given epoch reach similar conclusions. This line of reasoning leads to a variation of the gravitational constant, G, over cosmic time of order: $\frac{\dot{G}}{G} \sim \mathrm{H}_0 \sim 10^{-10}$ yr^{-1}, where H_0 is the Hubble constant quantifying the local expansion of the universe. (Study of the variation of fundamental constants must consider dimensionless forms involving products of the constant in question with $\hbar$, m_p, and c, since dimensionless quantities are invariant under coordinate transformation, for example: $\gamma \equiv \frac{Gm_p^2}{\hbar c}$ or $\alpha \equiv \frac{e^2}{\hbar c}$ [2,3]. We use $\mathrm{H}_0 = 75$ km s^{-1} Mpc^{-1}, and a deceleration parameter, $q_0 = 0.5$.) A similar prediction on G comes from the Brans-Dicke equation relating mass/energy to a cosmic scalar field [4]. Variation of G at the Hubble rate has been ruled out by measurements of planetary orbits [3,5]. Gamow [6] speculated that the charge on the electron, e, or more precisely, the fine structure constant, α, varies and not G. This would lead to variation of the Rydberg constant and hence contribute to the observed redshift, z, of spectral features in distant objects normally attributed to the evolution of the four-dimensional (4D) cosmic scale factor. Finally, Sisterna and Vucetich [7] point out that stringent limits to the variation of physical constants support Einstein's strong equivalence principle, and hence provide "accurate verification" for general relativity as the correct low-energy theory of gravity.

The idea of cosmic variation of physical constants has been revisited with the advent of models unifying the forces of nature based on the symmetry properties of quantum dimensions, such as the Kaluza-Klein (KK) model, or the more general requirement of extra dimensions in superstring theory (SS) [8,9]. These extra dimensions have a scale factor, R, of order the Planck scale, $R \approx 10^{-33}$ cm, and manifest themselves only during the first instant of creation, corresponding to the Planck time, 10^{-43} sec after the big bang, or at energies above 10^{19} GeV. These compact dimensions quickly vanish during the cosmic expansion of our familiar 4D space-time, however they may still have observable consequences, since the constants of nature observed in 4D are the result of integration over the extra dimensions [9]. It has been hypothesized that a variation of R with cosmic epoch could lead to a variation of the physical constants measured in 4D [2,10]. In particular, the fine structure constant, α, is predicted to behave as R^{-2} in KK theories, and R^{-6} in SS theories [2,11]. Unfortunately, while the time dependence of the cosmic scale factor in 4D space-time is well understood in terms of Einstein's theory of gravity, there is no analogous prediction concerning the evolution of R in extra-dimensional theories. It is possible that R increases or decreases monotonically, or even oscillates, with cosmic time [10]. Still, a measurement of the cosmic evolution of α would provide qualitative supporting evidence for the existence of compact dimensions [12].

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Limits to the evolution of α include laboratory measurements [13], consideration of the abundances of radioactive isotopes [13], and consideration of fluctuations in the microwave background and other cosmological constraints [14,15]. The most stringent terrestrial measurement comes from the Oklo natural reactor, which occurred about 1.8 Gyr ago. The 95% confidence limit (2σ) from these calculations is $|\frac{\dot{\alpha}}{\alpha}| < 7 \times 10^{-17}$ yr^{-1} [16]. Calculations of primordial nucleo-synthesis allow for a maximum variation of $|\frac{\dot{\alpha}}{\alpha}| < 11 \times 10^{-15}$ yr^{-1} ([2,11], although see [17]). Accurate spectroscopy of absorption and emission lines from objects at cosmologically significant redshifts can be used to set limits on the evolution of physical constants [5,12,18–20]. Such studies lead to limits of [21,22]: $|\frac{\dot{\alpha}}{\alpha}| < 2 \times 10^{-15}$ yr^{-1}.

Drinkwater *et al.* [23] and Wiklind and Combes [24] have compared absorption by molecular rotational transitions at millimeter wavelengths to HI 21 cm absorption to determine the evolution of the product $Y \equiv g_p \alpha^2$, where g_p is the proton-to-electron magnetic moment. These cm and mm measurements have the potential advantage over optical spectroscopy in that spectral resolutions of 1 km s^{-1} or better are easily obtained, and the absorption lines themselves can be extremely narrow [24], with the ultimate limitation ($\approx 10^{-8}$) being the accuracy of the lab measurements of the transitions in question. Based on errors due to signal-to-noise alone, the current best limit (2σ) using this technique is $|\frac{\dot{\alpha}}{\alpha}| < 1 \times 10^{-15}$ yr^{-1}. However, these measurements have a potentially much larger uncertainty arising from possible differences in the velocities of the HI 21 cm and molecular absorbing gas within a given galaxy [12,21,24]. Velocity differences can arise both along a given line-of-sight, and also due to the fact that observations at very different wavelengths (e.g., mm versus cm) may probe different lines-of-sight due to frequency dependent spatial structure of the background source. If line-of-sight differences occur on kiloparsec (kpc) scales, then systematic velocity differences can arise due to the galaxian potential, and can be of order 100 km s^{-1} [25]. If line-on-sight differences can be limited to sub-kpc scales, then it can be argued that the residual uncertainty is likely to be of order 10 km s^{-1}, i.e., comparable to the typical velocity dispersion of the interstellar medium in galaxies [26].

In this paper we present observations of HI 21 cm absorption at intermediate redshifts using the technique of very long baseline interferometry (VLBI) [27]. These observations provide spatial resolutions of tens of milliarcseconds (mas), corresponding to sub-kpc spatial scales, and hence mitigate the potential problem of probing different lines-of-sight at different wavelengths. In the following analysis we will quote heliocentric redshifts, z, and differences in redshifts, Δz. In terms of observed frequency differences, $\Delta \nu_o$, source-frame velocity differences, Δv, and the variation of the physical quantity in question, ΔY: $\frac{\Delta Y}{Y} = \frac{\Delta z}{1+z} = \frac{\Delta \nu_o}{\nu_o} \sim \frac{\Delta v}{c}$.

We have observed the HI 21 cm absorption toward the cosmic radio sources 0218 + 357 and 1413 + 135 using VLBI techniques (Fig. 1). The source 0218 + 357 is a gravitationally lensed background radio source, and the absorption is by gas in the lensing galaxy [28,29]. The source 1413 + 135 is a radio loud AGN at the center

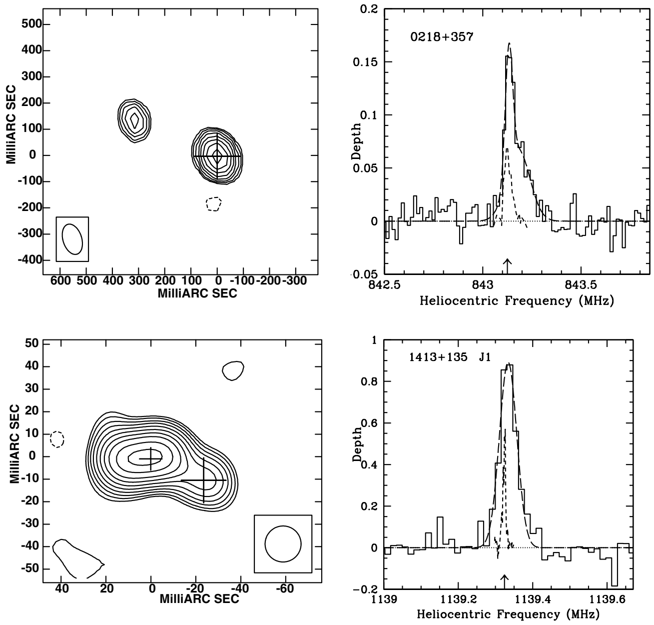

FIG. 1. The contour images (left) show total radio continuum surface brightness distributions for 0218 + 357 (top) and 1413 + 135 (bottom) derived from VLBI observations at the frequency of the redshifted HI 21 cm absorption lines. The observations of 0218 + 357 were made using the European VLBI Network in October 1998, while those for 1413 + 135 were made using the very long baseline array operated by the National Radio Astronomy Observatory during July 1998. The spatial resolutions are shown in the insets (FWHM). The total flux density of 1413 + 135 at this frequency is 1.2 Jy while that for 0218 + 357 is 1.8 Jy (1 Jy = 1×10^{-23} erg cm^{-2} s^{-1} Hz^{-1}). The contour levels are logarithmic in the square root two with an arbitrary absolute scale since no *a priori* gain calibration was applied due to lack of accurate system temperature measurements at these low frequencies. The spectra (right) show optical depth in redshifted HI 21 cm absorption toward the positions designated by the crosses in the continuum images. The solid line is the measured data, and the long dashed line is the Gaussian model fit. In the case of 1413 + 135, the position of the AGN is shown with the large cross, but the HI 21 cm absorption spectrum was made at the position of the peak surface brightness of the jet, corresponding to the smaller cross. The frequency scale has been corrected to a heliocentric rest frame. The short dashed lines show the CO absorption line profiles, scaled in frequency accordingly and on an arbitrary optical depth scale, as observed by the IRAM 30 m telescope (see [26], and references therein). The arrows indicate the expected HI frequencies based on Gaussian model fits to the molecular absorption lines. For 0218 + 357 the profile displayed is for CO(1-2), while that for 1413 + 135 is CO(0-1).

of an edge-on spiral galaxy, and the absorption is by gas in a molecular cloud in the disk of the parent galaxy [24,30]. The data were processed at the VLBA correlator in Socorro, NM, and images were generated using the Astronomical Image Processing System (AIPS). The data were fringe fit starting with a point source model for 1413 + 135 and a double source for 0218 + 357, and then imaged using standard hybrid imaging techniques [27]. In each case spectral data image cubes of 256 channels over 4 MHz bandwidth were analyzed. The details of the observations and their astrophysical implications will be presented elsewhere. Herein we concentrate on the information relevant to constraining the evolution of α.

For 0218 + 357 the continuum image has a resolution of 80 mas, corresponding to a physical scale of 390 pc, and shows two lensed radio components separated by 350 mas. We find that the dominant HI 21 cm absorption line is toward the southwest component. This is also true for the molecular absorption [31]. We have fit a two component Gaussian model to the absorption spectrum using a least squares algorithm. The principal component has a peak optical depth, $\tau = 0.12$, and a full width at half maximum, FWHM = 15 km s^{-1}, at a redshift of $z = 0.684\,676 \pm 0.000\,005$. The error corresponds to a change in z leading to a unit change in reduced χ^2. The peak of the molecular absorption in this system is at $z = 0.684\,693 \pm 0.000\,001$ [24], hence the difference between the molecular and HI 21 cm redshifts is $\frac{\Delta z}{1+z} = 1.0 \times 10^{-5} \pm 3 \times 10^{-6}$.

For 1413 + 135 the continuum image has a resolution of 20 mas, corresponding to a spatial scale of 70 pc, and shows a core-jet morphology extending over 60 mas. The position of the inverted-spectrum nucleus is shown as a large cross, and again, at mm wavelengths only the nuclear radio component is detected [32]. At 1143 MHz the jet dominates the total radio continuum emission from 1413 + 135. The absorption spectrum at the peak surface brightness of the jet, indicated by a small cross, is shown in Fig. 1. The sensitivity of these observations is insufficient to detect absorption toward the weaker nuclear radio component. We fit the spectrum of the jet with a one component Gaussian model, resulting in $\tau = 0.89$ and FWHM = 15 km s^{-1}, at $z = 0.246\,693 \pm 0.000\,001$. The molecular absorption in this system is extremely narrow (FWHM $\approx$ 1 km s^{-1}) with a peak at $z = 0.246\,709\,1 \pm 0.000\,000\,3$ [24], hence the difference between the molecular and HI 21 cm redshifts is $\frac{\Delta z}{1+z} = 1.3 \times 10^{-5} \pm 8 \times 10^{-7}$.

The errors given above are 1σ strictly based on the fitting process and the signal-to-noise ratio (SNR) in the observed spectra. There are a number of other systematic errors in the measurement and Gaussian fitting process which must be considered, including: (i) the transfer of the sky frequencies from the telescopes through the correlator to the data reduction programs, and (ii) the interpolation process when deriving redshifts to accuracies better than the spectral channel width of 15 kHz, including possible variations in the zero intensity level, the number of Gaussians used in the modeling, and the assumption of a Gaussian shape for the line profile. The results indicate that the measurement errors other than SNR are <10 kHz, corresponding to 3 km s^{-1}, or $\frac{\Delta z}{1+z} < 1 \times 10^{-5}$.

The sum total of the uncertainties discussed above are comparable to the most accurate astronomical measurement to date [21,22], and could be improved with higher SNR, higher spectral resolution observations. However, there remains the possibility of systematic velocity offsets between the HI 21 cm absorbing gas and the molecular absorbing gas in a given galaxy. Drinkwater *et al.* [23] demonstrate that the velocity of HI 21 cm absorption in the Galaxy shows a statistical correlation with that of molecular absorption, with a dispersion of only 1.2 km s^{-1}. On the other hand, there are clearly Galactic and extragalactic examples in which significant velocity differences occur [24], and a statistical analysis of the type in Ref. [23] will be rigorously valid only when applied to a statistical sample of absorbers. Note that this error does apply to calculations of $\frac{\dot{\alpha}}{\alpha}$ based on fine structure absorption doublets by alkaline metals [22].

For 1413 + 135 the molecular and HI 21 cm absorption spectra are narrow in velocity, suggesting absorption by the general ISM of the host galaxy. But the HI 21 cm absorption occurs along a line-of-sight toward the jet which is offset from that toward the nucleus by 25 mas. This line-of-sight offset will give rise to a velocity difference less than 10 km s^{-1} as long as the absorbing gas is beyond 0.5 kpc from the nucleus, assuming a flat rotation curve for the galaxy with a velocity of 200 km s^{-1}. For 0218 + 357 the absorption is again narrow, and our VLBI observations probe a region of diameter <390 pc through a face-on spiral galaxy [28]. In summary, it is reasonable to assume that the dominant uncertainty between the molecular and HI 21 cm redshifts in both 1413 + 135 and 0218 + 357 is due to small-scale (sub-kpc) ISM motions, i.e., $\approx$10 km s^{-1}. A velocity uncertainty of 10 km s^{-1} leads to a limit to the evolution of the fine structure constant of $|\frac{\dot{\alpha}}{\alpha}| < 3.5 \times 10^{-15}$ yr^{-1} to a look-back time, t, of 4.8 Gyr for 0218 + 357, and $|\frac{\dot{\alpha}}{\alpha}| < 6.7 \times 10^{-15}$ yr^{-1} to $t = 2.5$ Gyr for 1413 + 135, assuming that g_p is constant [33]. These limits are sufficient to rule out hypotheses D and E summarized in Dyson [3], in which $\alpha \propto t$, and $\alpha \propto \log(t)$, respectively.

In Table I we summarize the limits to $\frac{\Delta\alpha}{\alpha}$ over time, and to $\frac{\dot{R}}{R}$ in KK and SS theories. The most stringent limit to secular evolution of R remains the Oklo limit, although this limit has been called into question recently [7]. Hence, limits using other methods provide an important check of the Oklo limit. Also, all the limits taken together argue strongly against a slowly oscillating R with $\frac{\Delta R}{R} < 10^{-5}$ over the entire history of the universe. And the limits to $\frac{\dot{\alpha}}{\alpha}$ all have different functional dependencies on α and other physical constants. The lack of variation observed

TABLE I. Limits (2σ) to the evolution of the fine structure constant and the scale factor of compact dimensions. Quantities with redshifts are based on astronomical spectroscopy.

Method	z	Look-back time [Gyr]	$\frac{\Delta\alpha}{\alpha}$ [$\times 10^{-6}$]	$\frac{\dot{R}}{R}$ (SS) [$\times 10^{-6}$ yr^{-1}]	$\frac{\dot{R}}{R}$ (KK) [$\times 10^{-6}$ yr^{-1}]	Ref.
Laboratory	⋯	10^{-9}	4×10^{-8}	70	200	[13]
Oklo reactor	⋯	1.8	0.13	0.12	0.35	[16]
1413 + 135	0.25	2.5	17	11	33	This paper
0218 + 357	0.68	4.8	17	6	18	This paper
Radioactive elements	⋯	5	24	8	25	[11]
Fine structure	0.8	5.2	8	2.6	7.7	[22]
Fine structure	1.3	6.3	8	2.1	6.3	[22]
Metal + HI 21 cm	1.78	7.0	15	3.5	10	[21]
Primordial nucleosynthesis	⋯	8.9	100	18	55	[11]

for any of the different products of physical constants argues against models of a "cosmic conspiracy" in which the individual constants vary in concert to result in a given observable remaining invariant. One method for overcoming the uncertainty due to small scale ISM motions is to observe a large sample of sources (>100), and rely on the statistical correlation described in Drinkwater *et al.* [23]. Study of such a large sample will become possible only with the greatly increased sensitivity of the Atacama Large Millmeter Array, and the Square Kilometer Array.

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