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Limits on the Variation of Fundamental Atomic Quantities over Cosmic Time Scales

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The detection of Mg II fine structure and hydrogen hyperfine absorption lines toward the radio source AO 0235+164 allows us to place upper limits on the variability of three products of the fine-structure constant, the nuclear g factor of the proton, and the ratio of electron to proton mass, viz. $\alpha^2 g_p m/M$, $g_p m/M$, and α. Since the spectral lines are observed at a high red shift, $z = 0.5$, the limits obtained on the variation with time of these quantities (adopting z as a measure of the Hubble expansion) apply over at least 35% of the age of the universe.

Nearly forty years ago, Dirac[1] called attention to what he regarded as a remarkable coincidence between the magnitude of the dimensionless ratio of the electric and gravitational forces between an electron and a proton,

$$e^2/GMm = 2.3\times 10^{39}, \quad (1)$$

and the magnitude of the *present* age of the universe expressed in any quantity with the dimensions of time that can be constructed from fundamental atomic constants, e.g.,

$$T_0/(e^2/mc^3) \simeq T_0/(h/mc^2), \quad (2)$$

where T_0 [$=2.0\times 10^{10}$ yr for a Hubble constant $H_0 = 50$ km sec^{-1} Mpc^{-1} (pc stands for parsec)] is the age of the universe, and M and m are the proton and electron masses, respectively. Dirac speculated that either this coincidence was purely fortuitous or it reflects a causal relationship between the foundations of cosmology, gravitation, and electromagnetism. If the latter is true, then, because of the changing age of the universe, the coincidence can be preserved only if one (or more) of the fundamental constants varies with time.

Dirac suggested that perhaps the gravitational constant G was a function of time, but this idea is in conflict with the luminosity and lifetime of the sun.[2-4] Alternatively, Gamow[5] speculated that the unit of charge e evolves with the universe, but again this proposal can be dismissed either by arguments such as those given by Dyson[6] that involve the present abundance of the β-active isotope ^{187}Re relative to that of the stable isotope ^{187}Os, or by direct measurement of the fine-structure constant, α, in distant galaxies.[7,8]

The time variability of other fundamental quantities may be examined through the use of spectroscopic observations of extragalactic objects. Nearly all such objects show a red shift in both their continuum and line radiation. It is widely, though not universally, accepted that this red shift reflects the expansion of the universe. By adopting this interpretation here we have available to us information on atomic transitions, and hence the values of various fundamental parameters which govern these transitions, over a time interval corresponding to a significant fraction of the age of the universe. The specific, and presently unique, case we consider is the radio source AO 0235+164, a BL Lac-type object with a red shift $z \simeq 0.5$. This example is unique because it is the only high-red-shift object in which the hydrogen 1420-MHz hyperfine as well as (optical) fine-structure lines have been detected. The H line has been detected[9] in one other high-red-shift object ($z_H \simeq 0.7$), 3C286, but in this case no other absorption lines are seen.

The tests, which are described below, involve (a) a comparison of the hydrogen hyperfine frequency with the frequency of a resonance line for an alkalilike atom (Mg^+) at two epochs, the radio-source absorption and laboratory. This yields a limit on the time variation for the product $\alpha^2 g_p(m/M)$ [see Eqs. (6)–(9)], where α is the fine-structure constant and g_p is the nuclear g factor for the proton. The tests also involve (b) a comparison of the hydrogen hyperfine frequency and the Mg^+ fine-structure separation; from this we obtain a limit on the constancy of the product $g_p(m/M)$ [see Eq. (11)]. Finally, (c) from the observed separation of the Mg^+ fine-structure doublet we obtain information on α alone [see Eq. (12)]. This last test has been made previously[7,8] from astronomical data.

The pertinent observational data are the red shift measured[10] from the Mg^+ lines, $z_{Mg} = \Delta\lambda/\lambda_0 = 0.523\,92 \pm 0.000\,10$; the observed wavelength of either Mg line, 4260.5 ± 0.3 Å ($\lambda_{1ab} = 2795.53$ Å) and 4271.5 ± 0.3 Å ($\lambda_{1ab} = 2802.70$ Å) corresponding to Mg II $^2S_{1/2}$-$^2P_{1/2}$ and $^2S_{1/2}$-$^2P_{3/2}$; and the H red shift $z_H = \Delta\lambda/\lambda_0 = \Delta\nu/\nu = 0.523\,85 \pm 0.000\,01$. All red shifts are heliocentric.[11] The uncertainty in the optical wavelength measurements follows from the red shifts derived from eight different absorption lines detected[10] in this source. This uncertainty of ± 0.3 Å that we have adopted is consistent with the spectral resolution used for these observations.[12] This value so dominates the errors in laboratory wavelengths and in the 21-cm red shift that it is used solely for error estimates; all such estimates are taken to contribute linearly.

We may express the hyperfine splitting of the hydrogen ground state as[13]

$$\tilde{\nu}(\mathrm{H}) \simeq \frac{16\alpha^2 R}{3}\left(\frac{g_p\mu_n}{g_s\mu_0}\right)\left[1-\frac{3m}{M}+O\left(\frac{m^2}{M^2}\right)+\ldots\right]\left[1+\frac{\alpha}{\pi}+O(\alpha^2)+\ldots\right]\ \mathrm{cm}^{-1}, \tag{3}$$

and the wavelength of either member of the Mg II doublet as

$$\tilde{\nu}(\mathrm{Mg}^+) \simeq (RZ^2/n^2)[1+O(\alpha^2)+\ldots]. \tag{4}$$

Here R is the Rydberg constant for an infinite-mass nucleus, and

$$(g_p\mu_n/g_s\mu_0) = g_p m/2M, \tag{5}$$

is the ratio of the magnetic moments of the proton and electron.[13] The ratio

$$\tilde{\nu}(\mathrm{H})/\tilde{\nu}(\mathrm{Mg}^+) \simeq \mathrm{const}\,\alpha^2(g_p m/M)(1-3m/M+\ldots) \tag{6}$$

depends on the product of the ratio of the masses of the electron and proton and g_p and α^2 at any epoch.

Specifically, if we compare the ratio (6) determined in AO 0235+164 with that found in the laboratory, then

$$\frac{\tilde{\nu}(\mathrm{H})^*}{\tilde{\nu}(\mathrm{Mg}^+)^*}\left(\frac{\tilde{\nu}(\mathrm{H})}{\tilde{\nu}(\mathrm{Mg}^+)}\right)^{-1} = \frac{1+z_{\mathrm{Mg}}}{1+z_{\mathrm{H}}}, \tag{7}$$

where the asterisk superscript denotes quantities at the absorption epoch, and z_{Mg} and z_H are the red shifts determined from the Mg II and H 21-cm lines, respectively. Omitting higher-order terms in α^2 and m/M as well as quantities $\ll 1$, we find that

$$[(\alpha^2 g_p m/M)]^* = (\alpha^2 g_p m/M)[1.000\,05 \pm 0.0001], \tag{8}$$

where the estimated error follows from the quoted error in z_{Mg}.[10] To calculate the look-back time to the absorption epoch, we will assume that the absorption z is completely cosmological. This red shift may, however, contain a significant Doppler component if the gas is ejected with high velocity from AO 0235+164 at an earlier epoch corresponding to the cosmological red shift of the source. The red shift of AO 0235+164 is certainly greater than 0.851, the second absorption red shift detected in this source,[10] and, therefore, the cosmological epoch $z = 0.524$ sets a safe lower limit on the look-back time to the absorber. If we use the Friedmann cosmology with deceleration parameter $q_0 = 0$, the look-back time is $\geq 0.7\times 10^{10}(50/H_0)$ years so that the rate of change of $(\alpha^2 g_p m/M)$ is

$$|d\ln(\alpha^2 g_p m/M)/dt| \leq 2\times 10^{-14}\ \mathrm{yr}^{-1}, \tag{9}$$

where d denotes the change between the absorption epoch and the present. To our knowledge this is the lowest limit presently available on the variation of fundamental atomic quantities over cosmological time scales and obtains over approximately 35% of the age of the universe.

It is obvious from Eq. (9) that an upper limit on any one quantity cannot be set independently. If we choose, for example, to test the hypothesis that m/M varies in time, we cannot dismiss the possibility that either of the other two quantities, g_p (an expression of the internal structure of the proton) or α^2 (the quantum electrodynamical coupling constant) may also vary. Although we have no reason to rule out such a possibility, a tight compensatory balance is clearly demanded if variability exists. We note that (8) places a constraint on any theory which holds that large red shifts are not a measure of the expansion of the universe but rather reflect changing atomic constants.

We may also use the separation of the Mg II doublet in AO 0235+164 together with the red shift of the hydrogen absorption line to determine a limit on the variation of $g_p m/M$. The fine-structure splitting of an alkali atom, viz. in this instance the $3p^2P$ level of Mg^+, is

$$\Delta\tilde{\nu}(\mathrm{Mg}^+) \simeq \alpha^2 Z^4 R/2n^3\ \mathrm{cm}^{-1}. \tag{10}$$

Noting that both hyperfine- and fine-structure splittings are proportional to α^2 we find by an argument similar to that used in deriving Eq. (9) that

$$\left|\frac{d\ln(g_p m/M)}{dt}\right| \leq \left\{\frac{(1+z_{\mathrm{Mg}})^2}{(1+z_{\mathrm{H}})}\,\frac{\Delta\lambda(\mathrm{Mg\,II})}{\Delta\lambda(\mathrm{Mg\,II})_0} - 1\right\}(\Delta t)^{-1} \leq 8\times10^{-12}\ \mathrm{yr}^{-1}, \tag{11}$$

where $\Delta\lambda\,(\mathrm{Mg\,II})$ is the wavelength separation of the Mg II doublet in the laboratory. This limit is less significant than that in Eq. (9) because the latter depends on the percentage error in the observed wavelength whereas (11) depends on the percentage error of a wavelength difference. In obtaining the limit (11) we have used the observed splitting $\Delta\lambda\,(\mathrm{Mg\,II})_0$; had we instead used only the red shift z_{Mg} and assumed that it was distributive, i.e., $\Delta\lambda\,(\mathrm{Mg\,II})_0 = (1+z_{\mathrm{Mg}})\Delta\lambda\,(\mathrm{Mg\,II})$, the limit (11) would be identical to that in Eq. (9).

Finally, we may use the Mg II red shift together with the observed splitting in the Mg II doublet to place a limit on the variation of the fine-structure constant. Combining Eqs. (4) and (10) and proceeding as before, we find

$$|d\ln\alpha/dt| \leq 4\times10^{-12}\ \mathrm{yr}^{-1}, \tag{12}$$

where again we have directly employed the observed value of the splitting $\Delta\lambda\,(\mathrm{Mg\,II})_0$; in this instance if we had instead used only the observed red shift, $\Delta\lambda\,(\mathrm{Mg\,II})_0 = (1+z_{\mathrm{Mg}})\Delta\lambda\,(\mathrm{Mg\,II})$, the limit would be $\leq 1\times10^{-14}\ \mathrm{yr}^{-1}$. While the limit in Eq. (12) does not improve on previous work by Bahcall and co-workers,[7,8] it does restrict the volume of parameter space available to the quantities appearing in the limit (9).

Finally, we emphasize that the limits which we have obtained were made possible by the detection, for the first time, of a highly red-shifted 21-cm absorption line at the red shift of the identified optical absorption lines. The astronomical implications of this result are discussed elsewhere.[10,11]

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