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Implications of quasar spectroscopy for constancy of constants

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Given that the redshifts of quasars are due to the universal expansion, the details of their spectra can be used to check the constancy of certain dimensionless ratios of physics over look-back times comparable with the Hubble time and distances exceeding that of the particle horizon in the Einstein–de Sitter universe. With α, g_p, g_e, m_p, m_e denoting the fine structure constant, and the gyromagnetic ratios and masses of protons and electrons respectively, the following upper limits to variability over such times and distances have been derived in this way:

effect	quantity	approximate 3σ upper limit to variation
optical doublet splittings	α	3%
comparison of optical and 21 cm redshifts	$\alpha^2 g_p m_e/m_p$ (or $\alpha^2(g_p/g_e)(m_e/m_p)$)	10^{-3}
comparison of hydrogen and metal redshifts	m_e/m_p	50 %

1. Introduction

The purpose of this short paper is to review the contribution made by astrophysical observations of the spectra of distant galaxies and quasars to the placing of limits on the past variability of certain dimensionless ratios of physics: specifically, the fine structure constant α, the electron: proton mass ratio $m_e{:}m_p$ and the gyromagnetic ratio g_p of the proton (or more strictly its ratio to the corresponding value g_e of the electron), all of which enter the expression for the energy level shift due to hyperfine structure. The limits on possible variability are not as impressive as those derived from certain terrestrial measurements, in particular those of the Oklo phenomenon (Shlyakhter 1976; Irvine 1983), but in compensation they take us over large look-back times corresponding to redshifts z of up to 2.5 or more (compared with $z \approx 0.4$ for the epoch of origin of the solar system and $z \approx 0.15$ for Oklo); furthermore, they enable us to compare parts of the universe that may be causally unconnected with one another, and from a philosophical viewpoint this could be the most interesting part.

2. Constancy in time

While there is, by now, a wealth of literature on quasars that could be used to carry out elaborate statistical analyses if desired, there have in fact been only a few investigations specifically directed to testing for variability of atomic constants, presumably because interest has tended to be damped down by the consistently negative results of such experiments (cf. Dyson 1972; Yahil 1975). In the 1960s Bahcall and collaborators (Bahcall & Salpeter 1964; Bahcall *et al.* 1967;

Bahcall & Schmidt 1967), in response to a suggestion by Gamow that α (representing the electronic charge) might increase proportionally to time in such a way as to satisfy Dirac's 'large numbers' hypothesis, showed that this idea was ruled out by the existence of unchanged relative doublet splittings of optical emission lines due to [O III] and [Ne III] in radio galaxies with $z \approx 0.2$ and of ultraviolet (in the rest frame) absorption lines of Si II and Si IV in the QSO 3C 191 with $z = 1.95$. (QSO emission lines are unsuitable for this game because they are too broad.) These and many other more recent data (especially for C IV $\lambda 1548.20$ and 1550.77) indicate that α is indeed constant with a standard error of about 1 % for redshifts up to 2.5 or so, i.e. look-back times between 0.7 and 0.85 of the age of the Universe if $0 < \Omega < 1$ and $\Lambda = 0$.

Ten years later, Wolfe *et al.* (1976) studied the BL Lac object AO 0235+164 and discovered a 21 cm absorption line of HI having precisely the same redshift of about 0.5 as the ultraviolet doublet of Mg^+ previously identified in the optical spectrum by Burbidge *et al.* (1976). Since the hyperfine splitting (in Rydbergs) is proportional to

$$\alpha^2 (g_p/g_e)\,(m_e/m_p) \quad \text{or} \quad \tfrac{1}{2}\alpha^2 g_p (m_e/m_p),$$

their results place a tight limit on the past variability of this product with a 1σ uncertainty of 3×10^{-4} of itself in a Hubble time. Soon afterwards, I undertook an analysis of the component m_e/m_p in that product, by looking for a differential mass shift between hydrogen and metal lines with redshifts between 2.1 and 2.7. The ratio $m_e : m_p$ was found to be the same as now with a standard error of about 10 % (Pagel 1977) which, when combined with the previous result for hyperfine splitting, places a similar limit on the gyromagnetic ratio g_p of the proton and on the strong interaction effects that bring it about, assuming $g_e = 2$ always.

3. Constancy in causally unconnected parts of the Universe

In an extension of their 21 cm redshift studies to three other sources, Tubbs & Wolfe (1980) pointed out the significance of making observations of highly redshifted objects in different directions in the sky. Such objects can either be causally disjoint from one another, in that their co-moving separation exceeds the radius of the past light cone at all times since the big bang, or at least be so far apart that any one source is in causal contact with large tracts of space–time that are themselves disjoint from other sources. They illustrated this situation with a diagram valid in an Einstein–de Sitter universe and showed that for all reasonable values of Ω their sample of four objects is a case of the latter type. It follows that large variations in the hyperfine splitting within the radius of any one horizon are ruled out to the extent that this quantity is affected by its value at other places within the quasar's past light cone; but if it is not so affected, then spatial variations are ruled out only in a much smaller volume bounded by the quasars themselves.

If, however, we leave the case of the 21 cm line and content ourselves with the lesser precision associated with α and m_e/m_p, then we can discuss absorption-line systems of such high redshift that we could have a case of the first kind in which the objects themselves (really the clouds producing the absorption lines) are causally disjoint from one another, because their separation θ exceeds the critical separation θ_0 given by

$$2 \sin \tfrac{1}{2}\theta_0 = [(1+z)^{\frac{1}{2}} - 1]^{-1}; \quad z > 1.25,$$

in the Einstein–de Sitter universe (J. D. Barrow, personal communication). Examples taken from Pagel (1977) and elsewhere are listed in table 1 and many more could be added to these

TABLE 1. SELECTED QUASARS HAVING ABSORPTION LINE SYSTEMS WITH LYMAN α AND C IV

quasar	z_{abs}	θ_0/deg	θ/deg from 1623	reference†
PHL 957 (0100+13)	2.31 2.66 1.72	75.2 66.4 100.7	127	1
0551–37	1.96	87.9	159	2
0736–06	1.91 1.93	90.2 89.3	123	2, 3
1623+27	2.05 2.09 2.24	84.1 82.6 77.4	—	4

† 1, Coleman *et al.* (1976); 2, Young *et al.* (1982); 3, Carswell *et al.* (1976); 4, Sargent (1982).

which from CIV splittings and hydrogen-metal line concordance satisfy the constraints on variability already given. The situation is quite analogous to that of the uniformity of causally disjoint sources of the microwave background (see, for example, Tubbs & Wolfe 1980; Rees 1982) and it suggests (if $\Omega_0 \geqslant 0.5$ or so) that the constants had their present values impressed on them at a very early stage before the present expansion phase of the Universe.

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