Using quasar microwave spectra to study variation of fundamental constants

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Plan of the talk

1. Present limits on time-variation of fundamental constants
   - Atomic clocks
   - Geophysics: Oklo natural nuclear reactor, Gabon
   - Astrophysics: quasar UV absorbtion spectra
2. Sensitivity of astrophysical observations to variation of fundamental constants
   - Sensitivity coefficients
   - Limits from microwave and far infrared transitions
   - Further perspectives
3. Conclusions

Laboratory tests

If we have two atomic clocks their frequencies are likely to have different dependence on α and on m_p/m_e. By comparing these frequencies at different times we can look for time-variation of a certain combination x of α and m_p/m_e, $x \equiv \alpha^\nu (m_p/m_e)^\mu$.

• Typical time scale of such experiments is of the order of one year, compared to 10^{10} years in astrophysics.

• Typical accuracy of the frequency measurements is about 10^9 – 10^{10} times higher than in astrophysics.

• No isotope effects and other systematic effects are well controlled.

• Laboratory tests are complementary to astrophysical tests because they measure $\dot{x}/x$, not $\Delta x/x$.

Laboratory limits

Results of several most recent laboratory experiments based on comparison of pairs of atomic clocks.

Group, year		Limit	Clocks used	
		$10^{15} \times \dot{\alpha}/\alpha\ \mathrm{yr}^{-1}$		
Fortier *et al.*	(2007)	-0.55 ± 0.95	^{133}Cs	^{199}Hg$^+$
Peik *et al.*	(2006)	-0.26 ± 0.39	^{171}Yb$^+$	^{199}Hg$^+$
Cingöz *et al.*	(2006)	-2.7 ± 2.6	^{163}Dy	^{162}Dy
Fischer *et al.*	(2004)	-0.9 ± 2.9	H	^{199}Hg$^+$
		$10^{15} \times \dot{x}/x\ \mathrm{yr}^{-1},\ x = g_{\mathrm{nuc}} m_e/m_p$		
Fortier *et al.*	(2007)	3.0 ± 5.7	^{133}Cs	^{199}Hg$^+$

Oklo reactor

It is generally recognized that some 1.8 billion years ago (the respective redshift $z = 0.14$) a natural nuclear reactor operated in Oklo uranium mine in Gabon.

In 1976 Shlyakhter realized that respective nuclear reactions depended on the balance between the strong-interaction energy and the electromagnetic energy. He concluded that when Oklo reactor was operational α was very close to its present value.

Limits on time-variation from Oklo

In the most recent analyzes of data from Oklo the following limits were obtained:

$$\frac{\dot{\alpha}}{\alpha} = 10^{-17}\mathrm{yr}^{-1} \times \begin{cases} +0.3 \pm 1.0 & \text{Gould } et\ al.(2006) \\ -0.5 \pm 3.5 & \text{Petrov } et\ al.(2006) \end{cases}$$

These result depends on a number of assumptions. In particular, it is assumed that strong coupling constant did not change in time, which is unlikely if α was changing.
Flambaum and Shuryak (2007) argue that Oklo does not allow to place any restriction on α-variation. Instead they place the limit on $X_s \equiv m_s/\Lambda_{\mathrm{QCD}}$:

$$\left|\dot{X}_s/X_s\right| \le 10^{-18}\mathrm{yr}^{-1}$$

Astrophysical results for α-variation

Recent observations of the UV absorbtion lines of atomic ions in quasar spectra led to following restrictions on the possible α-variation:

$$\frac{\Delta\alpha}{\alpha} = 10^{-5} \times \begin{cases} -0.57(11) & \text{Murphy } et\ al. (2003) & 0.2 < z < 3.7 \\ -0.04(30) & \text{Srianand } et\ al. (2004) & 0.4 < z < 2.3 \\ -0.06(6) & \text{Quast } et\ al. (2004) & z = 1.15 \\ +0.54(25) & \text{Levshakov } et\ al. (2007) & z = 1.84 \end{cases}$$

The time-scale: $z = 0.2$ corresponds to 2 Gyr and $z = 3.7$ corresponds to 12 Gyr, assuming the lifetime of the Universe being 13.8 Gyr.

Astrophysical results for μ-variation

It is well known that mass ratio $\mu = m_p/m_e$ determines relative scales of electronic, vibrational, and rotational intervals in molecular spectra: $E_{el} : E_{vib} : E_{rot} \sim 1 : \mu^{-1/2} : \mu^{-1}$.
This relation was used in many astrophysical surveys of optical spectra of H_2, which placed increasingly stringent limits on time-variation of μ. However, the most recent publication by Reinhold *et al.* [PRL, **96**, 151101 (2006)] suggests non-zero variation at 3.5σ level:

$$\delta\mu/\mu = (20 \pm 6) \times 10^{-6},$$

at the time scale of approximately 12 Gyr. Assuming linear variation with time this result translates into

$$\dot{\mu}/\mu = (-17 \pm 5) \times 10^{-16}\ \mathrm{yr}^{-1}.$$

Big bang nucleosynthesis and cosmic microwave background

Different authors analyzed the big bang nucleosynthesis (BBN) and the anisotropy of the cosmic microwave background (CMB) and gave limits for the α-variation at these epochs, which correspond to the redshifts $z \sim 10^{10}$ and $z \sim 10^3$ respectively. These limits appear to be model-dependent, but are typically on the order of:

$$\frac{\Delta\alpha}{\alpha} \lesssim 10^{-2}.$$

Typical linewidths

The linewidth Γ in astrophysics is usually determined by the Doppler effect, i.e.

$$\frac{\Gamma}{\omega} = \frac{\Delta v}{c}.$$

For extragalactic observations typical velocity spread Δv is about $1 - 10$ km/c, which means that:

$$\frac{\Gamma}{\omega} \sim 10^{-5}.$$

$\Rightarrow$ For extragalactic objects the Doppler broadening limits accuracy of individual frequency measurements to the relative errors about $\delta\omega/\omega \sim 10^{-5}$. When we are looking for variation of fundamental constants, we can increase sensitivity by averaging over large number of lines from different species.

Sensitivity coefficients

Let us define dimensionless sensitivity coefficients K_i:

$$\frac{\delta\omega}{\omega} = K_\alpha \frac{\delta\alpha}{\alpha} + K_\mu \frac{\delta\mu}{\mu}\,.$$

In optical transitions in atoms typical sensitivity coefficients are:

$$10^{-2} \lesssim |K_\alpha| \lesssim 10^{-1}; \qquad |K_\mu| \lesssim 10^{-3}\,.$$

In optical transitions in molecules typical sensitivity coefficients are:

$$10^{-2} \lesssim |K_\alpha| \lesssim 10^{-1}; \qquad 10^{-3} \lesssim |K_\mu| \lesssim 10^{-2}\,.$$

Apparent redshifts

If we observe the transition ω_0 at the frequency ω, we determine the apparent redshift:

$$z' = \frac{\omega_0}{\omega} - 1\,.$$

Because of the variation of the fundamental constants the apparent redshift is different from the actual redshift z:

$$\frac{z' - z}{1 + z'} = -K_\alpha \frac{\delta\alpha}{\alpha} - K_\mu \frac{\delta\mu}{\mu}\,.$$

Comparing apparent redshifts of different transitions we can estimate the variation of fundamental constants:

$$\frac{\Delta z'}{1 + z'} = -\Delta K_\alpha \frac{\delta\alpha}{\alpha} - \Delta K_\mu \frac{\delta\mu}{\mu}\,.$$

$$\frac{\Delta z'}{1+z'} = -\frac{\Delta F}{F}, \qquad F = \alpha^{\Delta K_\alpha} \mu^{\Delta K_\mu}\,.$$

Sensitivity coefficients II

Transition	K_α	K_μ
Optical and UV range		
typical E1-transition in atom	$\lesssim 10^{-1}$	$\lesssim 10^{-3}$
electronic transition in molecule	$\lesssim 10^{-2}$	$\lesssim 10^{-2}$
Microwave and IR range		
fine-structure M1-transition	2	0.0
vibrational transition	0.0	-0.5
rotational transition	0.0	-1.0
21 cm hyperfine line in hydrogen	2.0	-1.0
18 cm Λ-doublet line in OH	-2	-3
1.25 cm inversion line in NH_3	0.0	-4.5

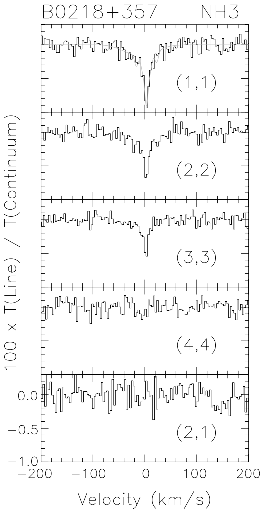
Published microwave and far infrared results

Authors	Year	Transitions		z	F	$10^6 \times \frac{\Delta F}{F}$
Varshalovich & Potekhin	1996	Optical	rot.	2.3	μ	60 ± 370
				1.9		70 ± 100
Murphy *et al.*	2001	hyperfine	rot.	0.68	$\alpha^2 g_p$	1.6 ± 5.4
Kanekar *et al.*	2005	Λ-doublet	rot.	0.68	$\alpha^{3.1}\mu^{1.6}$	0.4 ± 1.1
Flambaum & Kozlov	2007	NH_3 inversion	rot.	0.68	μ	0.6 ± 1.9
				0.68	α	-0.2 ± 1.0
				0.68	g_p	2.0 ± 5.8
Levshakov *et al.*	2008	C II fine-str.	rot.	6.42	$\alpha^2\mu$	10 ± 100

Ammonia lines in astrophysics

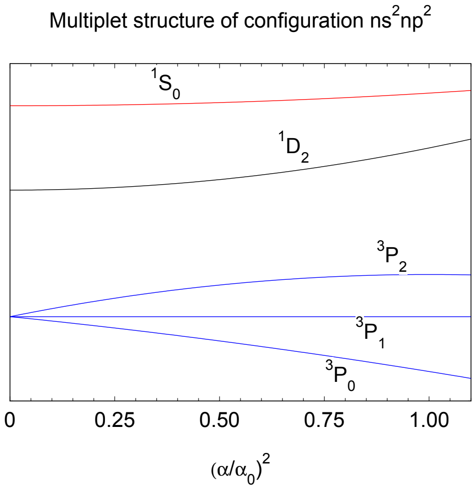
The most distant object, where inversion lines of NH_3 are seen is the galaxy B0218+357 at the redshift $z \approx 0.68466$, which corresponds to the look back time about 6 Gyr.

Fig. Inversion ammonia lines $\omega_{\rm inv}(J,K)$ [Henkel *et al.* Astronomy and Astrophysics, **440**, 893 (2005)].



- The relative errors for NH_3 inversion lines are $\delta\omega/\omega \approx 8 \times 10^{-6}$ ($\Delta v \approx 2$ km/s). They are statistically dominated. New generation of radio telescopes will allow to significantly reduce these errors.
- Present relative error for the fine-structure line of C II is $\delta\omega/\omega \approx 1 \times 10^{-4}$, or $\Delta v \approx 30$ km/s. Higher statistics can improve this error by up to two orders of magnitude.
- In order to reduce systematic errors from the Doppler noise, one needs to use different lines of the same species.
- In the case of NH_3 it is possible to compare inversion line with rotational, or vibrational line of NH_3. At present rotational lines of different molecules are used.
- In C I, S I, etc., there are two transitions between the fine-structure sub-levels of the ground state ^3P. In the lowest order in α, the sensitivity coefficients for both of them are the same, $K_\alpha = 2$. In the next order $\Delta K_\alpha \approx 0.008$ for C I and $\Delta K_\alpha \approx 0.12$ for S I.

Sensitivity to α-variation and Landé-rule



Atoms and ions with configuration ns^2np^2: C I, N II, Na VI, Si I, S III, etc.

Atoms and ions with configuration ns^2np^4 (inverted multiplet): O I, Ne III, Mg V, Si VII, S I, Ar III, etc.

Conclusions

- Search for time-variation of α and $\mu = m_p/m_e$ allows to test theoretical models beyond the standard model.
- There is no decisive evidence of α- and/or μ-variation, but there are some hints for that from astrophysics.
- Sensitivity of observations in microwave and IR ranges is 1-2 orders higher, than in optics.
- The most stringent limit on time-variation of μ follows from astrophysical spectra of ammonia. Comparison of FS line of C II with rotational line of CO gives the limit on time-variation of $\alpha^2\mu$ at $z = 6.42$.
- Laboratory test are slightly less sensitive than astrophysical tests, but their sensitivity is rapidly improving.