Clusters of galaxies and variation of the fine structure constant

Silvia Galli

IAP-Paris


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Testing the validity of known physics

- Fundamental Constants characterize theories, they are only **empirically measurable** and **not theoretically predictable**.
- Testing for variation of constants allows to test validity of known physics.
- Many probes, ranging from laboratory to astrophysical probes.

E.g. **Fine Structure Constant** (strength e.m. force)

- Claim of a space-time variation of $\alpha$ in quasars. (Webb et al. 2004, 2011)
- **From Pre-Planck CMB constraints at 2% (0.5% in combination)** (Menegoni et al. 2009 etc...)
- **Planck alone CMB constraint at 0.4%!**
New probe of variation of fine structure constant

Clusters can be observed through:

**SZ effect:** Clusters leave an imprint in the CMB spectrum as the hot gas inverse Compton scatter CMB photons.

**X-rays:** Clusters at T>2 KeV mainly emit through Bremsstrahlung effect.

From both, one can estimate quantities proportional to the thermal energy of the cluster.
Ysz and the fine structure constant

- Spectral distortion due to the SZ effect is proportional to the \( y \) parameter. This is proportional to the thermal pressure integrated along the line of sight.

\[
y = \frac{\sigma_T}{m_e c^2} \int n_e(r) T(r) dl
\]

- From \( y \), estimate of the thermal energy \( Y_{sz} \).

\[
Y_{SZ}^{sp}(R) D_A^2 = \frac{\sigma_T}{m_e c^2} \int_0^R n(r) T(r) 4\pi r^2 dr
\]

- Depends on Thomson scattering cross-section

\[
\sigma_T = \frac{8\pi}{3} \left( \frac{\hbar^2}{m_e^2 c^2} \right) \alpha^2
\]
$Y_X$ is the estimate of the thermal energy from X-rays.

$$Y_X = M_{g,500} T_X \propto \alpha^{-1.5}$$

- Observed surface brightness
- Deprojected emission per unit volume
- Density profile
- Gas Mass

$\epsilon_\nu = \alpha^3 \frac{2^5 \pi \hbar^3}{3m_e} \left( \frac{2\pi}{3m_e k} \right)^{1/2} Z^2 g_f f n_e n_i T^{-1/2} e^{-h\nu/kT}$
Ysz/Yx and the fine structure constant

SZ effect → Inverse Compton scattering → $Y_{sz} \alpha^2$

X-ray emission → Bremsstrahlung effect → $Y_x \alpha^{-1.5}$

\[
\left( \frac{Y_{SZ} D_A^2}{Y_X} \right)_i = \left( \frac{\alpha_i}{\alpha_0} \right)^{3.5} \left( \frac{Y_{SZ} D_A^2}{Y_X} \right)_0
\]

- The method proposed is **ROBUST** only for **NULL** constraints!!!!!

- **IF** the ratio is **constant** from cluster to cluster, the constraint on the constant ratio can be projected as a constraint on the fine structure constant.

- **IF** the ratio **varies** in time/space, it will be due to gas dynamics/systematics or maybe fine structure constant, but it will be very hard to disantangle.
Constant ratio

Clusters Thermal Energy

An additional constant term representative of the unaccounted intrinsic scatter is quadratically added to error bars. This scattering term is estimated directly from the data, imposing that the reduced $\chi^2$ of the fit must be 1.
New probe of variation of fine structure constant

• With 62 clusters from the Planck ESZ-sample between $0.04<z<0.44$ observed by Planck in SZ and XMM-Newton in Xrays,

\[ \frac{D_A^2 Y_{500}}{C_{XSZ} Y_X} = 0.97 \pm 0.027 \quad \sim 3\% \text{ constraint} \]

• This translates in a constraint on alpha of:

\[ \sigma(\alpha/\alpha_0) = 0.8\% \]

• Comparable to CMB constraints today ($\sim 0.4\%$) (but at completely different redshift range).

Future improvements

Current constraints are not limited by the uncertainty on cosmological parameters. However, with an arbitrarily large sample of clusters, the constraint on $\alpha$ attainable would be (assuming cosmology constrained by pre-Planck data):

$$\sigma(\alpha/\alpha_0) = 0.3\%$$

Using future Planck+Euclid data, a constraint using 2000 cluster could be:

$$\sigma(\alpha/\alpha_0) = 0.3\%$$

Back-up slides
Is the Ratio Constant?

\[
\frac{Y_{SZ} D_A^2}{Y_X} = C_{XSZ} \frac{\int n_e(r)T(r)dV}{T_X(R) \int n_e(r)dV} \sim const
\]

\[
\frac{D_A^2 Y_{500}}{C_{XSZ} Y_X} = \frac{1}{Q} \frac{\langle n_e T \rangle_{R_{500}}}{\langle n_e \rangle_{R_{500}} T_X}
\]

\[
Q = \frac{\sqrt{\langle n_e^2 \rangle_{dr}}}{\langle n_e \rangle_{dr}}
\]

**From theory:** if clusters evolution only due to gravity, scaling relations are self-similar and temperature/density/pressure profiles are universal.

**From Simulations:** the Yx-Ysz is predicted to be self-similar, with a low scatter at ~10-15%.

**From observations:** Excluding the inner core (where gas dynamics affects cluster characteristics), density/temperature profiles are observed to be universal at low-z, specially for relaxed clusters.
Evidence for spatial variation of the fine structure constant

J. K. Webb¹, J. A. King¹, M. T. Murphy², V. V. Flambaum¹, R. F. Carswell³, and M. B. Bainbridge¹

¹School of Physics, University of New South Wales, Sydney, NSW 2052, Australia
²Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Mail H39, PO Box 218, Victoria 3122, Australia and
³Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, England.

(Dated: August 25, 2010)

We previously reported observations of quasar spectra from the Keck telescope suggesting a smaller value of the fine structure constant, α, at high redshift. A new sample of 153 measurements from the ESO Very Large Telescope (VLT), probing a different direction in the universe, also depends on redshift, but in the opposite sense, that is, α appears on average to be larger in the past. The combined dataset is well represented by a spatial dipole, significant at the 4.1σ level, in the direction right ascension 17.3 ± 0.6 hours, declination −61 ± 9 degrees. A detailed analysis for systematics, using observations duplicated at both telescopes, reveals none which are likely to emulate this result.

PACS numbers: 06.20.Jr, 95.30.Dr, 95.30.Sf, 98.62.Ra, 98.80.-k, 98.80.Es, 98.80.Jk

FIG. 1. All-sky plot in equatorial coordinates showing the independent Keck (green, leftmost) and VLT (blue, rightmost) best-fit dipoles, and the combined sample (red, centre), for the dipole model, $\Delta \alpha / \alpha = A \cos \Theta$, with $A = (1.02 \pm 0.21) \times 10^{-5}$. Approximate $1\sigma$ confidence contours are from the covariance matrix. The best-fit dipole is at right ascension $17.4 \pm 0.9$ hours, declination $-58 \pm 9$ degrees and is statistically preferred over a monopole-only model at the $4.1\sigma$ level. For this model, a bootstrap analysis shows the chance-probability of the dipole alignments being as good or closer than observed is 6%. For a dipole+monopole model this increases to 14%. The cosmic microwave background dipole and antipole are illustrated for comparison.
Fine structure constant Dipole from Quasars

Webb et al. 2010
Variation of the fine structure constant
The Fine Structure Constant

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The Fine Structure Constant ?
The Fine Structure Constant and the CMB

• The CMB tests time-scales that are completely different from the one tested in laboratory.

• CMB is particularly sensitive to the evolution of the visibility function, which heavily depends on the value of $\alpha$. 
Variation of The Fine Structure Constant

\[ g(a)dz = \dot{\tau} e^{-\int \dot{\tau} da} \]

- The fine structure constant modifies the visibility function through the thompson scattering rate and \( xe \):

\[ \dot{\tau} = x_e(a) n \sigma_T a \]

Free electron Fraction

Thompson scattering cross section

\[ \sigma_T = \frac{8 \pi}{3} \frac{\hbar^2}{m_e c^2} \alpha^2 \]

1
The Evolution of the Free Electron Fraction

\[ \frac{dx_e}{dt} = C_H \left[ \beta_H (1 - x_e) e^{\frac{B_1 - B_2}{K_B T}} - R_H n_p x_e^2 \right] \]

Ionization coefficient
\[ \beta_H \rightarrow R_H \]

Recombination coefficient
\[ R_H \rightarrow \sigma_{nl} \approx \alpha^{-1} m_e^{-1} f'(h \nu / B_1) \]

Ionization cross section nl state

Rate of decay 2s a 1s
\[ \Lambda_{2s} \propto m_e \alpha^8 \]

Constant K
\[ K = n_e \frac{\lambda_\alpha^3}{(8\pi H)} \]

Lyman-alpha
\[ \lambda_\alpha = 16 \pi \frac{\hbar}{(3m_e c^2)} \alpha^{-2} \]

Peebles coefficient
\[ C_H = \frac{1 + K \Lambda_{2s} (1 - x_e)}{1 + K (\beta_H + \Lambda_{2s}) (1 - x_e)} \]
Variation of free electron fraction with $\alpha$

Different values of $\alpha$ change the evolution of the free electron fraction.

They shift the redshift of recombination.

In particular, when $\alpha$ is smaller, recombination takes place later at smaller $z$.

(see e.g. Avelino et al., Phys.Rev.D64:103505,2001)
If the fine structure constant is smaller:

- Recombination is delayed, the size of the sound horizon \( r_s \sim c_s \eta_{\text{dec}} \) at recombination is larger, so peaks of the CMB angular spectrum are shifted at lower \( l \) (larger angular scales).
- The Frequency \( r_s \) of the oscillations is larger.
- Larger Silk Dampening Scale \( k_D \)