

Probing the Light Speed Anisotropy with respect to the Cosmic Microwave Background Radiation Dipole

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Abstract - We have studied the angular fluctuations in the speed of light with respect to the apex of the dipole of Cosmic Microwave Background (CMB) radiation using the experimental data obtained with GRAAL facility, located at the European Synchrotron Radiation Facility (ESRF) in Grenoble. The measurements were based on the stability of the Compton edge of laser photons scattered on the 6 GeV monochromatic electron beam. The results enable to obtain a conservative constraint on the anisotropy in the light speed variations $\Delta c(\theta)/c < 3 \times 10^{-12}$, i.e. with higher precision than from previous experiments.

1 Introduction

The study of the light speed anisotropy with respect to the dipole of the Cosmic Microwave Background (CMB) radiation as suggested in [1], is the modern analog of the Michelson-Morley experiment. CMB, besides being a unique cosmological messenger, also is determining the hierarchy of inertial frames and their relative motions, and is defining an "absolute" inertial frame of rest, i.e. the one where the dipole and quadrupole anisotropies vanish.

The dipole anisotropy of the temperature T of CMB without doubts is of

Doppler nature,

$$\frac{\delta T(\theta)}{T} = (v/c) \cos\theta + (v^2/2c^2) \cos 2\theta + O(v^3/c^3) \quad (1)$$

(the first term in the right hand side is the dipole term) and is indicating the Earth's motion with velocity

$$v/c = 0.000122 \pm 0.00006; v = 365 \pm 18 \text{ km s}^{-1},$$

with respect to the above mentioned CMB frame.

WMAP satellite's 1-year data defines the amplitude of the dipole 3.346 ± 0.017 mK and the coordinate of the apex of the motion (in galactic coordinates) [2]

$$l = 263.85^\circ \pm 0.1^\circ, b = 48.25^\circ \pm 0.04^\circ. \quad (2)$$

The errors are due to the calibration of the WMAP and will be improved in due course. This coordinate is in agreement with estimations based on the hierarchy of motions involving the Galaxy, Local group and Virgo supercluster [3].

The probing of *the anisotropy of the speed of light with respect to the direction of CMB dipole* therefore is a profound aim.

An experiment was proposed in [1] to check such a light speed anisotropy using the effect of inverse Compton scattering of photons on monochromatic electron beams. Originally the idea of using the Compton scattering of laser photons on accelerated electrons has been proposed in [4]. Estimations showed the feasibility for reaching high accuracies at available parameters of laser beams, as well as for highly monochromatic electrons produced in existing accelerators, such as SLAC, ESRF (Grenoble), TJNAF. Besides of methodical difference with other experiments such a test would reach accuracies higher than the existing limits.

Majority of performed measurements of the light speed isotropy were dealing with a closed path propagation of light (see [7] and references therein). Such round-trip propagation are insensitive to the first order but are sensitive only to the second order of the velocity of the reference frame of the device with respect to a hypothetical universal rest frame. Mossbauer-rotor experiments yield a one-way limit $\Delta c/c < 2 \times 10^{-10}$, using fast beam laser spectroscopy [8]. The latter using the light emitted by the atomic beam yield a limit $\Delta c/c < 3 \times 10^{-9}$ for the anisotropy of the one-way velocity of the light. Similar limit was obtained by Vessot et al. [9] for the difference in speeds of the uplink and the downlink signals used in the NASA GP-A rocket experiment to test the gravitational redshift effect. One-way measurement of the velocity of light has been performed using also NASA's Deep Space Network [10]: the obtained limits yield $\Delta c/c < 3.5 \times 10^{-7}$ and $\Delta c/c < 2 \times 10^{-8}$ for linear and quadratic dependencies, respectively. Another class of experiments dealt not with angular but frequency dependence of the speed of light. For the visible light and γ -rays the limit $(1.8 \pm 6) \times 10^{-6}$ was obtained, while the difference with the velocity of 11 GeV energy electrons v_e was $(c - v_e)/c = (-1.3 \pm 2.7) \times 10^{-6}$ (see [12]). The data on gamma ray bursters, sources located on cosmological distances, were used by Schaefer [11] to obtain strong limits for the variation of the speed of

light on frequency, namely $\Delta c(\nu)/c < 6.3 \times 10^{-21}$ was obtained for 30-200 keV photons of the flare GRB 930229.

Below we present the first results of the test of the isotropy of the one-way speed of light by means of the Compton effect [1] using the data obtained at GRAAL. The results obtained are not only methodically different from those of the above mentioned experiments but also provide stronger constraints on the light speed anisotropy in CMB frame.

2 Compton Scattering on Photons on Monochromatic Electrons

In the case of head-on Compton scattering of low energy photons and ultra-relativistic electrons, the energy dependence of the scattered photon versus angle in the laboratory frame is given as

$$E_\gamma = \frac{4\gamma^2 E_\ell}{1 + \frac{4\gamma E_\ell}{m_e} + \theta^2 \gamma^2}, \quad (3)$$

where θ is the angle between the scattered photon and the incident direction of the electron, γ is the Lorentz factor of the electron (11820 for 6.04 GeV electrons), E_ℓ is the energy of the incident photon and m_e is the mass of the electron (Fig.1). For visible light (514.5 nm) the maximum energy of the scattered photons ($\theta = 0$, usually called Compton Edge, CE) is at 1100 MeV, while for the u.v. light (several lines around 351 nm) the CE is at 1500 MeV.

If the energy of the ultrarelativistic monochromatic electron beams is kept stable with given accuracy, namely the beam energy is stable over a long time and not at an instantaneous measurement, the Compton edge variation will result in the estimation of corresponding light speed variation:

$$\beta d\beta = (1/\gamma^2) d\gamma/\gamma. \quad (4)$$

E.g. for $E = 6.04 \text{ GeV}$ and $\sigma_E/E \approx 10^{-4}$ one obtains:

$$d\beta \leq 10^{-12}.$$

3 Experimental set-up

In the experiment carried-out with the GRAAL facility, installed at the European Synchrotron Radiation Facility (ESRF), Grenoble, the γ -ray beam was produced by Compton scattering of laser photons off the 6 GeV electrons circulating in the storage ring (≈ 1 km circumference), over a 6.5 m long straight section [5],[6]. The angle between the incident laser light and the electron beam does not exceed 1° , given the geometry of the set-up, and has no measurable influence on the beam energy.

Photon energy was provided by an internal tagging system located right after the exit dipole of a straight section (Fig.1). Electron position was measured by a silicon microstrip detector (128 strips with a pitch of 300 μm and 500 μm

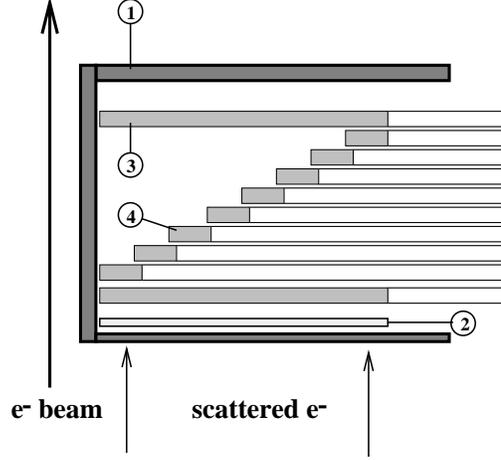


Figure 1: Schematic set-up of the tagging box: 1) X-ray shielding, 2) Si microstrip detector, 3-4) Scintillators and light guides for timing

thick). Two long plastic scintillators covering the whole focal plane (38.4 mm) and 8 small ones, each covering $\approx 1/8$ th, were situated behind the microstrip detector and provided a fast signal capable of separating 2 electrons of adjacent bunches (2.8 ns difference) and used as START signal in all Time of Flight (ToF) measurements of the experiment. The whole system was embedded in a 4π shielding box (equivalent to 8 mm Pb) against the huge X-ray back-ground. The thickness of this box and the minimum distance allowed to the electron beam determined our threshold of 650 MeV in gamma-ray energy.

The CE measured by the silicon microstrip detector is displayed on Fig.2 both for the visible and u.v. light provided by the laser. The CE is fitted for a given laser wave length by the function:

$$N(X) = a_1(1 + a_5X)(1 - \text{erf}(X)) + a_4 \quad (5)$$

for $X < 0$, and

$$N(X) = a_1(1 - \text{erf}(X)) + a_4 \quad (6)$$

for $X > 0$, where $X = \frac{x-a_2}{a_3\sqrt{2}}$ and where x is the position (expressed in microstrip number). The parameters a_1 to a_5 are fitted to the experimental spectrum, a_2 represents the CE position and a_3 the Gaussian parameter σ , a_1 is the amplitude, a_3 is the slope of the spectrum below the (CE) and a_4 is the residual gamma spectrum after the CE. The residual gamma spectrum is due to the Bremstrahlung of the electron beam. For u.v. three different groups of laser lines: 334.4, 351.1 and 335.8 nm, are present and can be seen on the experimental spectrum.

As shown in Fig.2, the experimental energy resolution can be extracted from the fit of the Compton edge, the theoretical distribution ending abruptly. In the case of u.v. lines (Fig.2 b) the three edges are clearly resolved and their peak position, width and relative intensity can be obtained. The measured resolution

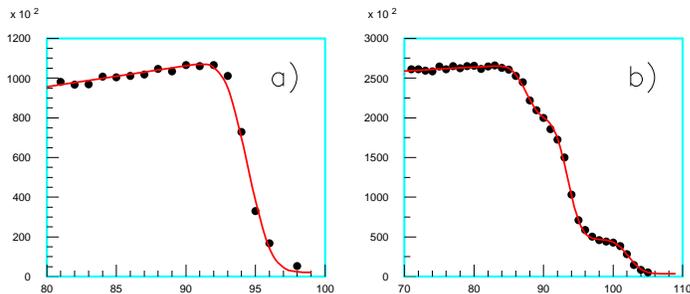


Figure 2: Analysis of the Compton edge for visible laser light (a) and u.v.light (b).

(FWHM \simeq 16 MeV) is in agreement with the estimated one from the simulation and is dominated by the electron beam energy dispersion (FWHM=14 MeV). The peak position is used to calibrate and monitor the absolute position of the microstrip detector whereas the relative laser line intensities are input to the calculation of the γ -ray beam polarization.

Typically an accuracy of $\simeq 0.03$ microstrip is obtained for the position of a given line (parameter a_2). This value corresponds to $\simeq 0.2MeV$ and thus:

$$\Delta E_\gamma / E_\gamma \simeq 2 \times 10^{-4}. \quad (7)$$

As a result 2075 measurements have been performed from 10.04.1998 to 11.05.2002 splitted in 48 periods of measurements.

4 Data Analysis

A special interactive software has been developed for the analysis of the GRAAL data. The data in our disposal have been represented via sequence of blocks with equal values of the Compton edge, as shown in Table 1.

For each block the extreme values, the dates of the start and the end of measurement are given in Table 1. The table shows also the distribution of the periods of measurements over months. All existing data have been studied by means of the normalization by dividing the Compton edge values of each of 48 initial data fragments. Variations both within 24 hour day and sidereal day have been studied.

Though large dispersion are apparent, see Figure 3, most of the experimental points are located within ± 0.3 microstrip and a stability with accuracy 2×10^{-3} can be estimated from the rough data.

Figure 4 shows the daily variations of data averaged within 1 hour intervals. The quasi-monotoneous increase of the average energy after the filling every 12

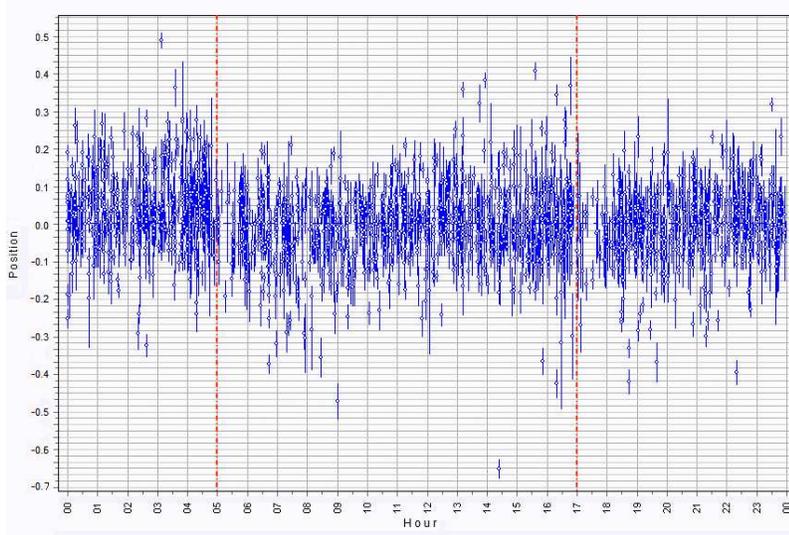


Figure 3: Experimental data plotted as a function of hour, showing their daily variation. The dispersion of data around the average, taken arbitrarily at zero, is expressed in fractions of microstrip (300 micrometers width or about 7 MeV for one microstrip).

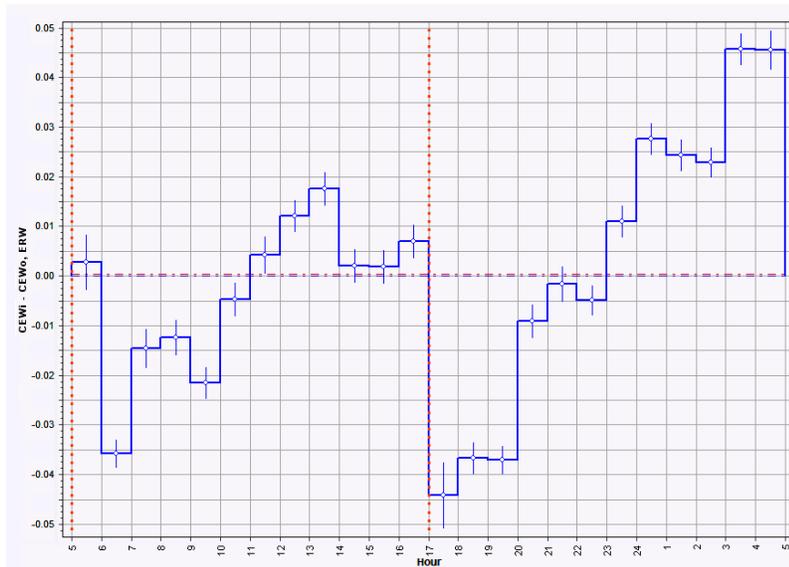


Figure 4: Same as figure 3 but each point is the average over one hour. The dotted lines show the refill time of the machine corresponding to a possible change in temperature of the tagging detector. The average is also expressed in microstrip fractions.

Block	CE position	Laser nm	Date of measurements	Total points	Months(1998-2002)/Number of measurements											
					I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	54.7-56.5	514.5	05.06.1999-05.02.2002	389	26	39	-	-	-	151	-	-	94	79	-	-
2	94.2-94.8	351.1	10.04.1998-21.09.1998	443	-	-	-	87	62	64	32	60	138	-	-	-
3	101.3-101.9	351.1	16.04.1999-16.05.1999	316	-	-	-	192	124	-	-	-	-	-	-	-
4	104.4-104.9	351.1	30.01.2000-06.03.2000	209	6	145	58	-	-	-	-	-	-	-	-	-
5	108.0-110.7	334.4, 351.1	15.04.2000-12.03.2002	329	-	39	69	97	8	-	-	-	-	-	116	-
Total	53.1-110.7		10.04.1998-11.05.2002	2075	32	261	180	546	256	215	32	60	298	79	116	-

Table 1: The dates of the different measurements which contribute to the final analysis.

hour (vertical bars) is clearly distinguished. This effect could be understood as a change in temperature of the beam vessel and therefore a change in position of the tagging box with respect to the beam. The correlation is obvious, but at a low level: 0.09 microstrip over 12 hours i.e. three times the uncertainty on a single measurement. However, this effect is averaged out at our main goal, i.e. when we look at the data as a function of CMB dipole.

The variation over the months is shown in Figure 5. Note the existence of up to 10 σ fluctuations for the individual points which we could not correlate to any systematic effect.

The distribution of all data averaged by month is given in Figure 6 together with the azimuthal angle value with respect to the direction of the CMB dipole. As can be seen in this plot the averaging procedure gives a very low values for the fluctuations, showing that the daily fluctuations observed in figure 4 are averaged out. From this plot we can estimate the fluctuations to $\simeq 0.015 \pm 0.007$ microstrip corresponding to

$$\Delta E_\gamma / E_\gamma \simeq (1 \pm 0.5) \times 10^{-4}. \quad (8)$$

The uncertainty is only statistical and reflects the averaging procedure.

5 Conclusions

From the stability limit obtained from figure 6, we can establish the following constraint for the light speed anisotropy $\Delta c/c \simeq (1 \pm 0.5) \times 10^{-12}$. The systematic errors of the experiment are indeed very difficult to estimate, thus in view of the large and unexplained fluctuations of the fitted value for the CE, we adopt a conservative value

$$\Delta c/c \leq 3 \times 10^{-12}. \quad (9)$$

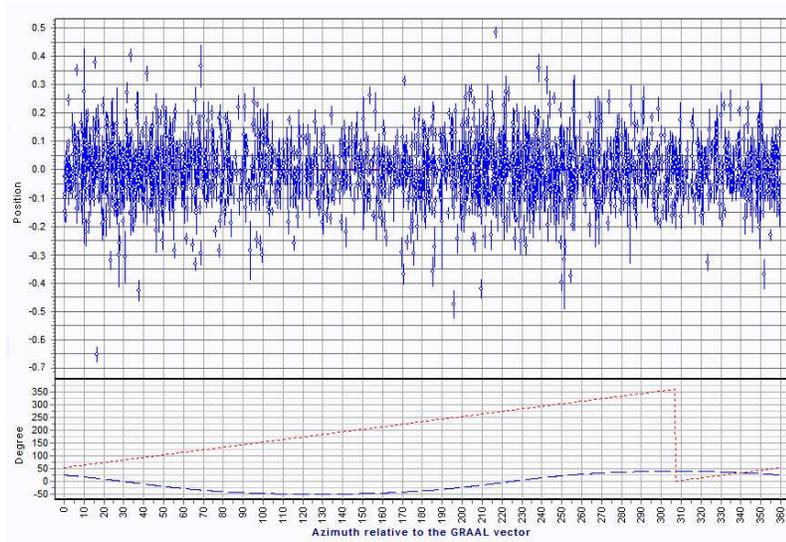


Figure 5: Experimental data plotted as a function of days, showing their variation over the year. Dispersion has the same expression than for the two previous figures.

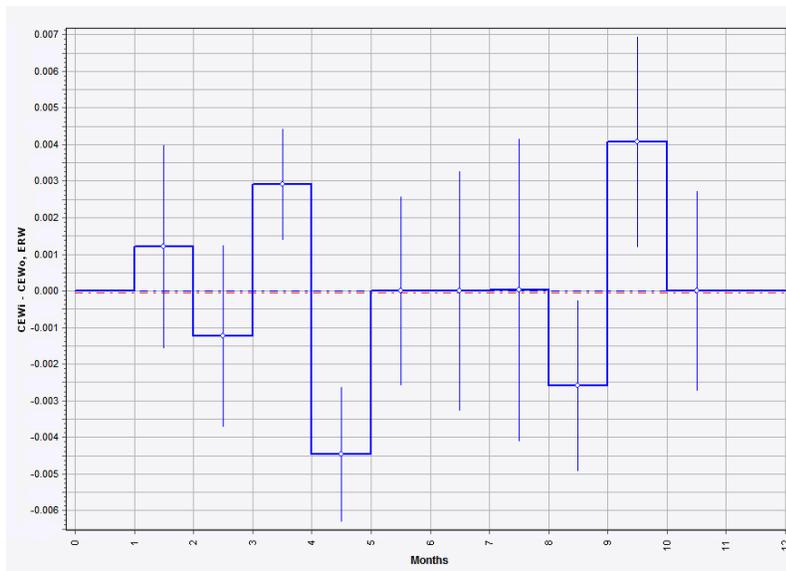


Figure 6: Same as figure 5 but each point is averaged over one month. The average, also expressed in microstrip fractions, is found very close to zero.

However, even this conservative limit is up to 3 orders of magnitude better than the one reachable from measurements involving the space probes (including the Cassini probe), since it will correspond to several meter accuracy of a planetary orbit, also it deals with one-way effect, while the space measurements are two-way one (Nordtvedt, personal communication, 2004).

It is important to note that, the electrons are circulating inside the machine at a rate of 10^6 revolutions per second, and therefore, an anisotropy effect cannot be compensated by the stabilization procedure of the machine as it could happen in a linear accelerator. In other words, the angle between the electron speed inside the ring and the direction of the CMB dipole is changing so fast, that the machine cannot compensate for a change in energy induced by an anisotropy.

Further studies of the light speed anisotropy, possibly in dedicated experiments, with respect to the apex of CMB with higher value of γ and lower value for $d\gamma$, seem rather crucial and can reduce our limit or give evidence for possible anisotropy effects.

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