Study of time lags in HETE-2 Gamma-Ray Bursts with redshift: search for astrophysical effects and Quantum Gravity signature

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1 - Motivations and Model

This study (see [1] for details) is based on a model developed in the framework of String Theory [2]. Gravitation is considered as a gauge interaction and Quantum Gravity effects result from graviton-like exchange in a background classical space-time.

The situation is represented in the figure on the right. (a) A graviton (closed string) propagates in an extra-dimension. (b) It interacts with a D-brane representing our Universe. (c) After the interaction, the graviton continues on its way. The D-brane is left in an excited state and gets a recoil movement.

This model leads to the fact that velocity of light depends on the energy of the photons:

\[ v(c) = \frac{E}{\sqrt{\Omega_a + \Omega_c(E)}} \]

Then, it is possible to write a dispersion relation for the velocity of photons. At the first order, this relation gives:

\[ v(c) = c \left( 1 - \frac{E}{\sqrt{\Omega_a + \Omega_c(E)}} \right) \]

This leads to the fact that two photons emitted at the same time with an energy difference \( \Delta E \) will be detected with a time lag \( \Delta t \).

In this work, we measure time lags for several Gamma-Ray Bursts (GRBs) observed by the satellite HETE-2 with different redshifts. Our goal is to detect a possible DG effect on light propagation.

As GRBs are at cosmological distances, the expression of \( \Delta t \) as a function of the redshift and energy gap \( \Delta E \) depends on the cosmological model. Following [3], the first-order time lag is given by

\[ \Delta t = H_0 \frac{\Delta E}{v(\Delta E)} \]

where \( v(\Delta E) = \int_0^{\Omega_c} \frac{dz}{\sqrt{\Omega_a + \Omega_c(z)}} \)

with \( \Omega_a = 0.7 \) and \( \Omega_c = 0.3 \).

2 - HETE-2 Fact Sheet

- **Operations:** October 2000 – November 2006
- **Mass:** 125 kg
- **Observed GRBs:** >250
- **Number of localised GRBs:** 120
- **Number of measured redshifts:** 24

- **Instruments:**
  1. **FREGATE (French Gamma-ray Telescope)**
  2. **HETE-2 (Wide Field X-ray Monitor)**
  3. **CCD Camera**

HETE-2 was dedicated to fast localisation of GRBs. It was primarily developed and fabricated in house at the MIT by a small scientific and engineering team, with major hardware and software contributions from international partners in France and Japan [4].

3 - The data

- 15 GRBs with 0.16 < z < 3.37.
- Use of FREGATE photon tagged data. Several energy bands scenarios are studied.

4 - Denoising and extreme localisation

- Wavelet transform is a multi-scale analysis method.
- Discrete Wavelet Transform (DWT) is used to remove the noise. Use of WaveLab [5].
- Continuous Wavelet Transform (CWT) is used to localise extreme points. Use of LavaWave [6].

5 - Noise

- Variance and mean of the background noise are obtained before the burst.
- Signal is studied only in the range where it is above 1\( \sigma_{\text{SS}} \). For GRB 030323, GRB 030429 and GRB 060526, a level of 0.5\( \sigma_{\text{SS}} \) is used.

6 - Selections

For each extremum, the derivative, the Lipschitz coefficient \( \alpha \) and its error \( \delta \alpha \) are computed and \( \alpha \) and \( \delta \alpha \) are obtained with the CWT. The Lipschitz coefficient is a measurement of the regularity of the signal.

7 - Results

- Time lags are first studied as a function of \( K_a \):

\[ \Delta t = K_a + b(1 + z) \]

This yields an estimate \( b \) of the intrinsic parameter \( b \).

- For each energy gap scenario, we define a \( \chi^2 \) function as a function of the energy scale \( M \):

\[ \chi^2(M) = \sum_{\text{extrema}} \left( \frac{\Delta t_{\text{obs}} - \Delta t_{\text{calc}}(M)}{\Delta t_{\text{SS}}^2} \right)^2 \]

\[ a(M) = \frac{\Delta t_{\text{SS}}^2 - \Delta t_{\text{calc}}(M)}{\Delta t_{\text{SS}}^2} \]

The best limit (95% CL): \( E_{\text{SS}} > 3 \times 10^{-17} \text{GeV} \)

8 - Conclusion and outlook

Light curves of 15 GRBs with known redshifts observed by the satellite HETE-2 have been studied using wavelet analysis in order to look for a Quantum Gravity effect on light propagation. No effects is detected above 3\( \sigma \) and a lower limit on \( E_{\text{SS}} \) is set to 2.9 \times 10^{-17} \text{GeV}.

This work will be extended to a larger sample of GRBs using an estimator for the redshift [7].

Notes and references:

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