Can the gamma-ray bursts travelling through the interstellar space be explained without invoking the drastic assumption of Lorentz invariance violation?

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Gamma-ray bursts (GRB) delay

- Experimental observation of

  gamma-ray bursts (GRB) delay

  (ANTARES experimental data taken 2007 – 2012)

  Adrian-Martinez et al (2018)

  with gamma ray energies analyzed up to 100 TeV has been interpreted as a sign of

  Lorentz invariance violation (LIV).

- But is this necessary when breaking Special Relativity but leaving General Relativity intact?

  We shall come to this later.

GRB and the disperssion of light in interstellar space

- Possibility of explaining GRB delay by standard physics - dispersion of light travelling through the interstellar space.
- Dispersion relation in a medium like electron plasma is:

$$\omega^2 = \omega_p^2 + k^2 c^2,$$

with

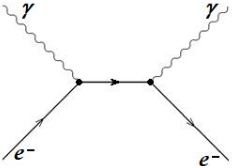
$$\omega_p^2 = \frac{Ne^2}{\varepsilon_0 m}$$

square of the plasma frequency, N is the mean number density of particles, ϵ_0 the permittivity in vacuum and m is the particle mass.

see, e.g., Jackson (book, 1999)
Chaichian, Merches, Radu, Tureanu (book, 2016)

- The same can be obtained in this limit from Quantum Field Theory/ Green function methods

see, e.g., Abrikosov, Gorkov and Dzyaloshinski (book, 1963)



$$\frac{e^2}{\not{q} - m_e} \simeq \frac{e^2}{m_e}$$

- With $m = m_e = 0.511$ MeV, one obtains for the group velocity :

$$v_{GRB} = \frac{d\omega}{dk} \simeq c\left(1 - \frac{\omega_p^2}{2\omega^2}\right) \equiv c(1-d).$$

- For the gamma-ray energy 1 TeV we get

$$v_{GRB} = c(1 - 0.7N \times 10^{-51})$$

Therefore, dispersive properties of an electron gas are not significant enough to account for a time delay of the order of several hours.

GRB and disperssion by axions

- Look for particles of much lower mass, like the

  AXIONS, with $m_{axion} = 10^{-5}\mathrm{eV}/\mathrm{c}^2$
- But non-charged axions favoured.
- Vivid activity in axion electrodynamics

  F. Wilczek (1987),
  Basar, Dunne (2003),
  A. Martin-Ruiz et al (2015),
  K. Fukushima (2019),
  CAST-CERN Axion Solar Telescope

  with its connection to topological insulators [CAST-CERN Axion Solar Telescope].
- Assumptions of an axionic plasma with its coupling to photons seems natural.

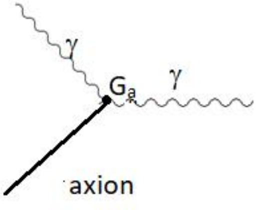
- Effective coupling of axion to two photons given by the interaction Lagrangian

Sikivie (2020),
Halverson et al (2019)

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_\gamma \frac{\alpha}{\pi} \frac{1}{f_a} a(x) F^{\mu\nu}(x) \tilde{F}_{\mu\nu}(x),$$

where

$$g_\gamma = \frac{1}{2}\left(\frac{N_e}{N} - \frac{5}{3} - \frac{m_d - m_u}{m_d + m_u}\right)$$



$$G_a \equiv g_\gamma \frac{\alpha}{\pi} \frac{1}{f_a}$$

- In GUT models

$$g_\gamma = \frac{m_u}{m_d + m_u} \simeq 0.36$$

- Estimate for G_a, the effective coupling constant,

$$G_a \equiv g_\gamma \frac{\alpha}{\pi} \frac{1}{f_a} \simeq 10^{-12} - 10^{-10}\ \mathrm{GeV}^{-1}$$

- In this case, dispersion of light in an axionic plasma, $\omega^2 = \omega_p^2 + k^2 c^2$, but now with

$$\omega_p^2 = N_{axion} G_a.$$

  N_{axion} means number density of axions in the cosmic plasma.

- Now with values: $G_a = 10^{-12}$ or $10^{-10}\ \mathrm{GeV}^{-1}$ and $N_{axion} = 10^{51}$ or $10^{49}\ \mathrm{m}^{-3}$, respectively, we get the delay for gamma–ray burst as

$$\tau = D \times d/c = 3.25\ \text{hours}$$

where D is the effective distance traveled by photons, deliberately taken as diameter of observable Universe, $D = 8.8 \times 10^{26}$ meters.

- N_{axion}:
  - clearly a function of its place in the medium, distance-dependent.
  - While nearby to us very high density not natural,
  - at very far distances in the stellar space, many heavy galaxies, N_{axion} by far larger/ axion coupling much enhanced
- Moreover:
  - The plasma frequency, ω_p, for axion medium, taken only from electric interaction contribution.
  - For electron plasma, no magnetic contribution: parity of medium.
  - For a "Chiral Medium" also magnetic field contribution ===> enhancement of G_a ===> reducing N_{axion}.
  - Such chiral medium with magnetic contribution affects the Casimir effect

Jiang and Wilczek (2019)

Lorentz invariance violation - interpretation of GRB delay

- A large activity in general, for GRB starting by

  Jacob and Piran (2007) and (2008)

- Special Relativity dispersion relation changed to

$$E^2 = c^2 p^2 - \epsilon c^4 p^4 + \sum_n a_{2n} p^{2n}$$

or typically for group velocity (up to 2nd term) as:

$$v_g = c\left(1 - \xi \frac{E}{E_{QG}}\right)$$

E_{QG} assumed as effective quantum gravity scale, usually taken $10^{16} GeV$, ξ arbitrary parameter.

Resolution between Cosmic Plasma and LIV interpretations

Cosmic plasma: $v_{GRB} = c(1 - 0.7N \times 10^{-51})$ or LIV: $v_g = c\left(1 - \xi \frac{E}{E_{QG}}\right)$?

Energy-dependence of delay:

- Cosmic plasma: higher-energy gamma rays —> less delay
- LIV: higher-energy gamma rays —> more delay.

Future experiments will resolve

see HAWC Collaborationv arXiv:1911.08070 [astro-ph.HE],
MAGIC Collaboration arXiv:2001.09728 [astro-ph.HE]

Neutrino bursts

- In **plasma case**:
  - Dispersion of neutrinos negligible.
  - Massive and oscillating : $E^2 = c^2p^2 + m^2c^4$

$$v_\nu = dE/dp \approx c[1 - m^2c^4/(2E^2)]$$

  - Averaging over 3 neutrinos: $\langle m^2c^4 \rangle = (1/3)(0.1eV)^2$,

$$v_\nu = c(1 - 0.17 \times 10^{-26}),$$

  justifying our taking $v_\nu = c$.

- In **LIV case**:
  Big questions, unless
  * dispersion relation for neutrino and photon are taken differently.
  * Special Relativity broken, General Relativity not, only quantum effect of it assumed.

Shedding light on the Abraham–Minkowski Controversy

- How to define the momentum of a photon propagating in a medium?
- Abraham (1909): momentum absolute value of $\mathbf{p}^{\mathrm{A}}$
  Minkowski (1908): absolute value of momentum $\mathbf{p}^{\mathrm{M}}$

$$E = |\mathbf{p}^{\mathrm{A}}|nc = |\mathbf{p}^{\mathrm{M}}|c/n,$$

- Although relation to Abraham–Minkowski dilemma looks remote, indeed formal correspondence right:
  photon energy $E = \hbar\omega$, $p = \hbar k$, with Minkowski momentum ===>

$$v_g = dE/dp^M = c/n < c.$$

Thus the Minkowski momentum favoured, also in accord with laboratory experiments conclusion.

Conclusions

- While we do not underestimate the interpretation of GRB delay by assuming LIV,
- we bring attention to the possibility of its explanation by standard physics of dispersion of light through a Cosmic Plasma, assuming it to be Axion Plasma.
- Future planned experiments shall resolve between the two possibilities.

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