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Are Gamma-Ray Bursts at Cosmological Distances Optically-Thin?

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ABSTRACT

The observed spatial distribution of γ -ray bursts indicates that they probably originate at cosmological distances. At this distance scale their variability timescale and flux above MeV imply an initial optical-depth to pair production $\gtrsim 10^{10}$. This appears to be in conflict with their highly non-thermal spectra. We show that this difficulty can be removed if axion bursts from supernovae are converted to γ -rays over cosmological distances. Nonthermal bursts with the relevant flux, duration, variability and spectra are obtained just for the range of axion masses of $10^{-5} - 10^{-4}$ eV that accounts for the cold dark matter in the universe. The observed rate of γ -ray bursts implies that axions should be converted efficiently to photons in only one out of $\sim 10^4$ supernovae.

The recent results from the BATSE experiment on board the Compton Gamma Ray Observatory^[1] indicate that the source distribution of γ -ray bursts (GRB) is non-Euclidean at low fluxes and isotropic. These observations rule out a galactic disk population, and suggest that GRB most likely^[2] originate at a cosmological distance D_H . The characteristic GRB flux F_γ then translates to a source luminosity (assuming isotropic emission),

$$L_\gamma \approx 10^{50} \frac{\text{erg}}{\text{sec}} \left(\frac{F_\gamma}{10^{-7} \text{erg/cm}^2 \cdot \text{sec}} \right) \left(\frac{D_H}{3 \text{Gpc}} \right)^2, \quad (1)$$

surprisingly close but smaller than the energy output of a hot neutron star. Moreover, the typical duration of bursts is similar to the cooling time of a hot neutron star. These coincidences, combined with the observed frequency of bursts ($\sim 2 \text{day}^{-1}$) led to the suggestion that coalescing neutron star binaries are the energy sources of GRB^{[3][4]}.

Without any reference to the origin of their energy supply, cosmological GRB face severe theoretical difficulties. Many of the bursts show variability on timescales shorter than a fraction of a second and must therefore originate from a source size $\lesssim 10^{10} \text{cm}$. With the characteristic photon flux above MeV, the optical depth for pair creation by photon-photon collisions is therefore $\gtrsim 10^{10} (D_H/3 \text{Gpc})^2$ at the source. The resulting fireball thermalizes quickly its electromagnetic energy supply and must therefore emit almost thermal radiation as it expands relativistically and eventually becomes optically-thin^[5]. This expected emission is in conflict with the flat energy spectra observed^[6] ($\nu I_\nu \approx \text{const}$ between $100 \text{keV} - 100 \text{MeV}$). Moreover, if the electromagnetic energy release is contaminated by more than $\sim 10^{-5} M_\odot$ of baryons the emerging photons will be degraded to low energies and the burst duration will be lengthened beyond the observed bounds³. This second constraint appears to be rather acute for realistic astrophysical environments, especially near the surface of a neutron star where neutrino heating can easily ablate $\gtrsim 10^{-2} M_\odot$ of baryons^[7]. In view of these model-independent difficulties, it seems worthwhile to consider novel physical processes that allow energy to be released in a weakly-interacting form and later be transformed to an electromagnetic form over cosmological distances, far away from the source. In this paper we explore the possibility that axions, produced in supernova events at cosmological distances, mediate the energy release in γ -ray bursts.

The axion was discussed extensively in the literature as the most attractive solution to the strong CP problem^{[8][9]} and as a potential cold dark matter candidate^[10]. The misalignment

production of axions results in a cosmological density parameter^[11]

$$\Omega_a = 0.2 \times 10^{\pm 0.4} h_{80}^{-2} g(\Theta_1^2) \Theta_1^2 \left(\frac{m_a}{10^{-5} \text{eV}} \right)^{-1.18}, \quad (2)$$

where m_a is the axion mass, h_{80} is the Hubble constant in units of $80 \text{km/sec} \cdot \text{Mpc}$, Θ_1 is the initial misalignment angle, $g(\Theta_1^2)$ is a function of order unity, and the error bars reflect theoretical uncertainties. Due to this highly non-thermal production, the universe is filled with a Bose-Einstein condensate of axions at almost zero peculiar momentum. This process allows the relatively light axion to serve as a potential cold dark matter candidate¹⁰.

The emission of axions by supernovae was discussed recently in detail^{[12][13][14]} in an attempt to constrain the axion properties after a neutrino burst was detected from SN1987A. The axion luminosity was found to be dominated by nucleon-nucleon bremsstrahlung. For $m_a \ll 10^{-2} \text{eV}$ the axions stream freely through the neutron star with a total luminosity^[15],

$$L_a \approx (2 \times 10^{50}) \times 10^{\pm 1.5} \frac{\text{erg}}{\text{sec}} \left(\frac{m_a}{10^{-4} \text{eV}} \right)^2 \left(\frac{T_{ns}}{30 \text{MeV}} \right)^{3.5}, \quad (3)$$

where T_{ns} is the mass averaged temperature of the neutron star. For the axion masses which account for the dark matter in the universe [Eq. (2)] the value of L_a coincides with the inferred luminosity L_γ of cosmological GRB [Eq. (1)]. Axions in the mass range of $10^{-5} - 10^{-4} \text{eV}$ affect only weakly the neutrino cooling rate of a hot neutron star, since $L_a \ll 10^{53} \text{erg/sec}$. Therefore, the duration ($\sim 0.1 - 10^2 \text{sec}$) and variability timescales ($\sim 0.1 - 10^4 \text{msec}$) of the resulting axion burst would be comparable to those of GRB^[16]. Since the neutron star is transparent to axions, their integrated bremsstrahlung emissivity would differ appreciably from a blackbody shape. The volume emissivity of axions makes the specific properties of their burst highly sensitive to the details of the collapse. In particular, significant non-sphericity, angular momentum, fragmentation, or magnetic fields are just a few of the available degrees of freedom that could control the specific properties of axion bursts and make them different from each other just like GRB. Although these ingredients are likely to affect the properties of the neutron star core in realistic circumstances, they are often ignored for computational convenience in stellar collapse codes. Motivated by the similarity of axion bursts and GRB, the remaining question is whether supernova axions can be converted to γ -rays due to their electromagnetic coupling as they travel across the universe. Radiative decay is irrelevant since the axion lifetime is $\sim 10^{45} (m_a/10^{-4} \text{eV})^{-5} \text{sec}$. Scattering of supernova axions on the cosmic background radiation can be induced by the

cosmological axion condensate (to a final axion state that coincides with the condensate and a scattered photon that carries most of the initial axion energy); however the total rate for this process is still small. A mechanism of potential importance is axion–photon conversion in the magnetic fields that surround the progenitor star or that are embedded in the interstellar or intergalactic media^{[17][18]}. Although this mechanism involves a variety of astrophysical degrees of freedom, there are difficulties in applying it using plausible physical conditions.

The frequency of GRB ($\sim 2\text{day}^{-1}$) implies that only $\sim 10^{-4}$ of all supernova events in the universe get efficient conversion of their axions to photons. It is therefore not surprising that SN1987A was not one of these rare events^[19]. The scarcity of bursts relative to supernovae may be linked either to the axion properties or to the external conditions responsible for the axion–photon conversion outside the supernova envelope. It could result, for example, from the fact that the axion is relatively light ($10^{-6} - 10^{-5}\text{eV}$) and has weak couplings, or that only a small fraction of all lines of sight are associated with magnetic environments that allow efficient axion–photon conversion. It is also possible that only rare phenomena, like binary coalescence (of neutron star–neutron star or neutron star–black hole systems), manage to provide the conditions necessary for bright bursts. If Type II supernovae follow each of the GRB, it would be possible to detect their light curve even at cosmological distances through dedicated optical searches. Their association with specific bursts requires that the positional error boxes of the bursts be $\lesssim (2^\circ)^2$, smaller in area by at least an order of magnitude than the error boxes provided by the Gamma Ray Observatory.

Axion bursts are expected to be deficient of low energy axions because of the effects of degeneracy blocking and collisional decoherence on the nucleons that produce them by bremsstrahlung^{12–14}. This is consistent with the lack of x-rays in GRB ($\lesssim 2\%$ of the total energy). Detailed calculations of the expected spectrum of axion bursts from hot neutron stars can be done from first principles. The spread in travel times across the universe of axions with different energies above E should be small, $\lesssim 2\text{msec } h_{80}^{-1} (m_a/10^{-4}\text{eV})^2 (E/\text{MeV})^{-2}$, and difficult to detect.

In conclusion, axion bursts from cosmological supernovae share the qualitative temporal and spectral characteristics of γ –ray bursts, provided axions are the cold dark matter in the universe. The specific process for converting supernova axions to γ –rays in one out of $\sim 10^4$ supernovae is still a missing link that must be identified in order that this association be viable. It would be remarkable indeed if the “invisible axion” revealed its existence in

γ -rays.

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