ON THE ORIGIN OF GAMMA RAY BURSTS

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We propose that repeated photoexcitation/ionization of high Z atoms of highly relativistic flows by star-light in dense stellar regions followed by emission of decay/recombination photons, which are beamed and boosted to \( \gamma \) ray energies in the observer frame, produce gamma ray bursts (GRBs). We show that this overlooked mechanism is able to convert efficiently baryonic kinetic energy release in merger or accretion induced collapse of neutron stars into cosmological GRBs and reproduces remarkably well all the main observed properties of GRBs.

The origin of gamma ray bursts (GRBs), which have been discovered 35 years ago, is still a complete mystery [1]. Their observed isotropy in the sky, deficiency of faint bursts and the lack of concentration towards the Galactic center, in the Galactic disk and in the direction of M31, strongly suggest [2] that they are cosmological in origin [3]. A cosmological origin implies [4] that GRBs have enormous luminosities during short periods of time,

\[
L \approx 10^{50} d_{28}^2 \phi_6 \Delta \Omega \text{ erg s}^{-1},
\]

where \( d = d_{28} \times 10^{28} \text{ cm} \) is their luminosity distance, \( \phi = 10^{-6} \phi_6 \text{ ergs cm}^{-2} \text{s}^{-1} \) is their measured energy flux, \( \chi \) is a bandwidth correction factor and \( \Delta \Omega \) is the solid angle into which their emission is beamed. Moreover, the short durations of GRBs imply very compact sources. Relativistic beaming is required then, both in order to explain the absence of accompanying optical light and X-ray emission, and in order to avoid self opaqueness due to \( \gamma \gamma \rightarrow e^+e^- \). All these considerations [4] seem to support the favorite cosmological model of GRBs; relativistic fireballs [5] formed by mergers of neutron stars (NS) or neutron stars and black holes (BH) in close binary systems [6] due to gravitational wave emission [7], or by accretion induced collapse (AIC) of NS and white dwarfs (WD) [6,8]. Indeed, the above considerations and the observed rate of GRBs favor NS mergers/AIC as the source of cosmological GRBs. Nevertheless, no mechanism has been convincingly shown to be able to convert a large enough fraction of their binding energy release into \( \gamma \) rays and to explain simultaneously the observed complex light curves, duration distribution and spectral behavior of GRBs [4].

Most of the binding energy released in NS mergers/AIC is expected to be in the form of neutrinos, gravitational waves and kinetic energy of ejected material [9]. No mechanism is known which converts efficiently gravitational waves into \( \gamma \) rays. Neutrino annihilation [6] \( (\nu\bar{\nu} \rightarrow e^+e^-) \), and neutrino pair production in strong magnetic fields \( (\nu\bar{\gamma}_v \rightarrow \nu e^+e^-) \) near merging/collapsing NS cannot convert enough binding energy into \( e^+e^-\gamma \) fireballs or relativistic \( e^\pm \) beams which can produce cosmological GRBs, because of baryon contamination [10] and the low efficiency of these processes [11]. Thus, if NS-NS and NS-BH mergers, or AIC of WD and NS, produce GRBs, the production must proceed through conversion of
baryonic kinetic energy of a highly relativistic flow (a fireball or a jet) into $\gamma$ rays. In this letter we propose that repeated photoexcitation/ionization of the highly relativistic atoms of the flow by star-light in dense stellar regions followed by emission of decay/recombination photons which are beamed and boosted to $\gamma$ ray energies in the observer frame (see Fig. 1), produce cosmological GRBs. We show that this simple mechanism, which has been overlooked, is able to convert enough baryonic kinetic energy of highly relativistic flows in dense stellar regions into cosmological GRBs. We also show that it predicts remarkably well the main observed properties of GRBs; their burst size, duration distribution, complex light curves and spectral evolution.

The surface of neutron stars is believed to consist of iron-like nuclei [9]. Therefore, we assume that the ejected mass in NS mergers or in AIC of NS or WD contains such high Z nuclei. In view of the uncertainties in modeling merger/AIC of compact stellar objects [11], rather than relying on numerical simulations, we deduce the total relativistic kinetic energy release in such events from observations of type II supernova explosions, which are driven by gravitational core collapse into NS or BH. In type II supernova explosions, typically, $10M_\odot$ are accelerated to a final velocity of $v \sim 10^4 \text{ km s}^{-1}$ [9], i.e., to a total final momentum $P \sim 10M_\odot v$. Since core collapse is not affected directly by the surrounding stellar envelope, we assume that in merger/AIC collapse of NS or WD a similar impulse, $\int F dt \approx P$, is imparted to the ejected mass. If the ejected mass is much smaller than a solar mass, $\Delta M \ll M_\odot$, then it is accelerated to a highly relativistic velocity and its kinetic energy is given approximately by $E_K \sim Pc \sim 6 \times 10^{53} \text{ erg}$. More than $10^{-3}$ of this highly relativistic baryonic kinetic energy must be converted into $\gamma$ rays in order to produce a typical cosmological GRB of $\sim 10^{51} \text{ erg}$.

The natural birth places of close binary systems are the very dense stellar regions in galactic cores and collapsed cores of globular clusters (GC). These GC regions have very large photon densities and column densities, $n_\gamma \sim 3L/4\pi c R^2 \epsilon$ and $N_\gamma \sim L/\pi c R \epsilon$, respectively. For instance, the core of our Milky Way (MW) galaxy has a surface brightness, $\Sigma \sim 1.2 \times 10^7 L_\odot \text{ pc}^{-2}$, typical photon energies, $\epsilon \sim 1 \text{ eV}$, and a radius, $R \sim 0.5 \text{ pc}$ [12]. These values yield, on average, $N_\gamma \sim 10^{23} \text{ cm}^{-2}$. (Actually, this value underestimates the column density because we have neglected the contribution from stars beyond $R$. Its inclusion yields $N_\gamma$ that are several times larger. A similar value is obtained for the nearby M31 galaxy. Much larger values are obtained for active galactic nuclei). The highly relativistic ejecta expands, cools and becomes transparent to its own radiation after a relatively short time [5]. Its partially ionized, highly relativistic atoms see the interstellar photons blue shifted to X-ray energies. These photons photoexcite/photoionize the high Z atoms of the flow which subsequently decay/recombine radiatively by isotropic X-ray emission in the flow’s rest frame. For a highly relativistic flow with a Lorentz factor $\Gamma \gg 1$, the isotropic X-rays are beamed along the flow, and as long as $\theta < 1/\Gamma$ their energies, $\epsilon_X$, are boosted to $\gamma$ ray energies,

$$\epsilon_\gamma \approx 2\Gamma\epsilon_X/(1 + \Gamma^2\theta^2),$$

(2)
where $\theta$ is the angle of the flow direction relative to the observer. The differential fraction of the emission that is directed towards the observer is given by

$$dI/d(\cos\theta) \approx 2\Gamma^2/(1 + 2\Gamma^2\theta^2).$$  \hspace{1cm} (3)

The total baryonic kinetic energy which is converted into beamed $\gamma$ ray emission by repeated excitation/decay can be estimated as follows: The total photoabsorption cross section of an atom in an atomic state $n$ into a state $n'$ is

$$\int \sigma_{\nu n n'} d\nu = \frac{\pi e^2}{m_e c} f_{nn'},$$  \hspace{1cm} (4)

where the integral is over the natural line width and where the oscillator strength $f_{nn'}$ satisfies the sum rule, $\sum_{n'} f_{nn'} = Z$, with $Z$ being the number of electrons in the system [13]. If the typical energy of the interstellar photons is $\epsilon \sim 1$ eV, and if their energy is boosted in the flow’s rest frame by a Lorentz factor $\Gamma \sim 10^3$, then their typical photoabsorption cross section by Fe atoms is

$$\bar{\sigma} \equiv \frac{\int \sigma_{\nu n n'} h\nu d\nu}{\Gamma \epsilon} = \frac{\alpha h}{2 m_e c} \frac{h\epsilon Z}{\Gamma \epsilon} \approx 3 \times 10^{-18} \text{cm}^2.$$  \hspace{1cm} (5)

This cross section is larger by about seven orders of magnitude than the typical cross sections for production of $\gamma$ rays in the interstellar medium by inverse Compton scattering, bremsstrahling and synchrotron emission by electrons, or by $\pi^0$ production by hadrons followed by $\pi^0 \rightarrow 2\gamma$ decay. Thus, if the ionized or excited atoms recombine/decay radiatively fast enough, then the typical energy of GRBs (burst size) from NS mergers/AIC in GC is given approximately by

$$E_\gamma \approx \bar{\sigma} N_\gamma (\epsilon_X/m_A) E_K \approx 3 \times 10^{51} \text{erg},$$  \hspace{1cm} (6)

where $m_A \approx 56m_p$. Note that the burst size is proportional to the total kinetic energy $E_K$ of the relativistic flow, and to the column density of the radiation field in the GC along the line of sight to the explosion, provided that the flow is not strongly attenuated by the radiation field. (If NS merger/AIC occurs near a bright active galactic nucleus, where $L \sim 10^{12}L_\odot$ and $R \sim 10^{17} \text{cm}$, i.e., $N_\gamma \sim 10^{29} \text{cm}^{-2}$, then a large enough fraction of the kinetic energy of the relativistic flow can be converted into a GRB even by inverse Compton scattering [14,15]. However, such a GRB will be extremely short and structureless).

Let us show that the relativistic atoms are only partially ionized. The recombination rate (radiative electron capture) of hydrogen-like atoms into the ground and excited states is given approximately by [13]

$$r \approx 4 \times 10^{-13} Z^2 T_{eV}^{-1/2} \text{cm}^3 \text{s}^{-1},$$  \hspace{1cm} (7)
where $T_{eV}$ is the temperature in eV in the flow rest frame. The ionization/excitation rate must adjust itself to the recombination/decay rate. Consequently, in the rest frame of the flow

$$n_{e11}T_{eV}^{-1/2} \approx c\Gamma n_{\gamma}\bar{\sigma} \approx 9n_{\gamma5}/\epsilon_{eV},$$

(8)

where $n_e = n_{e11} \times 10^{11}$, $n_\gamma = n_{\gamma5} \times 10^5$ and $\Gamma = \Gamma_3 \times 10^3$. Moreover, in its rest frame the relativistic flow expands against the external radiation field until its internal pressure equals the external pressure, i.e.,

$$n_e kT \approx \Gamma^2 n_{\gamma}\epsilon \text{ or } n_{e11}T_{eV} \approx \Gamma_3^2 n_{\gamma5}\epsilon_{eV}.$$

(9)

Consequently, $T_{eV} \approx [\Gamma_3\epsilon_{eV}/3]^{4/3}$ and $n_{e11} \approx 9^{2/3}\Gamma_3^{2/3}/\epsilon_{eV}^{1/3}n_{\gamma5}$. These rather low temperatures and high densities of the relativistic flows justify our initial assumption that the inner electronic shells of the relativistic Fe atoms are not ionized and the radiative decay/recombination is fast enough.

We have constructed a numerical Monte Carlo code which simulates the production of cosmological GRBs by highly relativistic flows in dense stellar regions [16]. The code employs the quantum mechanical cross sections for the relevant photo excitation/ionization and radiative recombination/decay processes. The core of the MW galaxy [12] was used for modeling the stellar environment (density of stars, stellar luminosities and stellar temperatures) in a typical GC. Initial distributions of Lorentz factors which are consistent with theoretical considerations and observations have been used. For instance, shock acceleration usually produces an approximate broken power-law spectrum of Lorentz factors, i.e.,

$$dn_A/d\Gamma \sim (\Gamma/\Gamma_m)^{-p} \text{ with } 1.5 < p < 2.5 \text{ for } \Gamma \geq \Gamma_m \text{ and } p < 0 \text{ for } \Gamma \leq \Gamma_m.$$ 

Using our GRB simulation code [16] we have found that (a) the main properties of the simulated GRBs are not sensitive to fine details and (b) the calculated light curves and spectral behavior of simulated GRBs reproduce remarkably well those observed in GRBs [1, 17-19]. In particular, the simulated GRBs look indistinguishable from the observed GRBs. This is demonstrated in Fig. 2 which compares a simulated GRB and a GRB from the BATSE 1B catalog [18] brought in [1] as an example of a typical complex GRB. Note that the temporal power spectra of the observed and the simulated GRB light curves have the same universal power-law behavior,

$$P(w) \equiv |\int L(t)exp(iwt)dt|^2 \sim w^{-2}.$$

This universal power-law behavior can be derived analytically [15,16] from our model. Here we summarize briefly approximate analytical derivations [16] of the other main observed properties of GRBs [1,17-19]. For the sake of simplicity we neglect here general relativistic effects (e.g., time dilation and energy redshift) and here that the explosions are spherical symmetric and occur at the center of the GCs, that the stars within a GC have a uniform spatial distribution, the same luminosity and the same effective surface temperature, and that the energy flux in the relativistic flow, $E^2dn_A/dE$, is peaked around a Lorentz factor $\Gamma$. Then our model predicts that:

1. GRB light curves are composed of a smooth background plus strong and weak pulses. Strong pulses are produced when the relativistic flow passes near stars within the “beaming
cone”, i.e., stars at an angle $\theta_s < 1/\Gamma$ relative to the line of sight from the explosion to the observer (see eq. 2). When a star is actually a multiple star system (binary, triplet, etc) the pulse becomes a multipeak pulse with very short separation in time between the peaks (spikes). Weak pulses are produced by boosting star-light from stars near the beaming cone. The smooth background is produced by boosting the background light in the beaming cone from all the other stars in the GC. Although the photoexcitation of partially ionized atoms produces line emission, the line emission is Doppler broadened into a continuum by the continuous distribution of the Lorentz factors of the atoms in the flow. Thus, the model predicts a continuous energy spectrum that at any moment has an approximate broken power-law form (see point 8) which depends on the energy spectrum of the relativistic atoms in the flow and on the spectral properties of the star-light which they boost. The ionization state of the atoms cuts off emission in the observer frame below $E_{\text{min}} \sim \Gamma m I \sim 5 - 25 \text{keV}$, where $I \sim \text{few} \times 100 \text{eV}$ is the ionization potential of the last bound electrons in the partially ionized atoms [16]. It explains why GRBs are not accompanied by detectable X-ray or optical-light emission.

2. The duration of a GRB reflects the spread in arrival times at the observer of gamma rays produced within the beaming cone (we neglect the short formation time of the relativistic flow because the dynamical time for NS merger/AIC is much shorter, typically 1ms). It is given approximately by

$$T \sim R/2c\Gamma^2. \quad (10)$$

Hence, relativistic flows with $\Gamma \sim 10^3$ in MW-like GC ($R \sim 0.5 \text{pc}$) produce GRBs that last typically 25 seconds. Thus, approximately a one light-year path in a GC is contracted into a ten seconds $\gamma$ ray picture in the observer frame.

3. The properties of the pulses from single stars depend on their locations, luminosities and spectra, and on the distribution of Lorentz factors in the flow. A pulse from a star at a distance $D_*$ and an angle $\theta_*$ begins at time $t_i \sim D_*\theta_*^2/2c$ after the beginning of the GRB ($t \equiv 0$). Its duration (while its intensity is twice the background) is given approximately by

$$T_p \sim D_*\theta_*d\theta_* \approx b/c \Gamma \sim L_*R/Lc\Gamma, \quad (11)$$

where $b$ is the impact parameter from the star at which the star’s light dominates the photon column density of the GC. For main sequence stars with $10^{-1} \leq L_* / L_\odot \leq 10^3$, $\Gamma = 10^3$ and MW-like GC we obtain $5 \text{ms} \leq T_p \leq 50 \text{s}$. For solar like stars $T_p \sim 50 \text{ms}$. Multiple stars yield multipeak pulses. For instance, the time difference between the two pulses from a binary star is given by

$$T_b \approx D_*\theta_*d\theta_*/c \approx d_p/\Gamma c , \quad (12)$$

where $d_p$ is the distance between the binary stars projected on the plane perpendicular to the flow. Thus, $T_b < 500(d_{\text{A.U.}}/\Gamma_3) \text{ms}$, where $d_{\text{A.U.}}$ is the binary separation in astronomical units. Since a large fraction of the stars are in close binaries, triplets, etc, a large fraction of the pulses have a multipeak structure.
4. In a GRB from a GC with $N_*$ stars uniformly distributed, the average number of stars within the beaming cone is $n_p \sim N_*/4\Gamma^2$. Thus, for a MW-like GC and $\Gamma \sim 10^3$, we expect, on average, $n_p \sim 3$ strong pulses.

5. The average rate of strong pulses in a GRB for a MW-like GC is $dn_p/dt \sim cN_*/2R \sim 0.1 \text{ s}^{-1}$, independent of time. The average time-spacing between the strong pulses, $\Delta T$, is given by,

$$\Delta T = T/n_p \sim 2R/cN_* \sim 10s.$$  

(13)

However, the time-spacing between successive pulses is predicted to fluctuate considerably around this average time-spacing.

6. If the spectrum of $\Gamma$ in the flow has a power-law form, $dn_\lambda/d\Gamma \sim \Gamma^{-p}$, then the energy spectrum of a strong pulse is given approximately by [16]

$$dn_\gamma/dE \sim \tilde{\sigma}(\Gamma)(dE/d\Gamma)^{-1}\Gamma^{-(p-1)}/(\Gamma\theta_* + 1/2)$$  

(14)

where $\tilde{\sigma} \sim \Gamma^{-(1+\delta)}$. For $\Gamma \gg 1/\theta_*$, $E \sim 2\Gamma\epsilon_X$, $\delta \leq 0.5$ one has $dn_\gamma/dE \sim E^{-(p+1+\delta)}$. For $\Gamma \ll 1/\theta_*$, one has [16] $E \sim \epsilon\Gamma^2$, $\delta \sim 0$, and then $dn_\gamma/dE \sim E^{-(p+1+\delta)/2}$. Hence the spectrum of a pulse has a broken power-law form. The break occurs when $2\Gamma\theta_* \sim 1$, i.e., around an energy $E_b \approx 2\Gamma\epsilon_X \approx \epsilon_X/\theta_*$. The power-index changes by $\sim (p + 1 + \delta)/2 \sim 1.5$ from well below the break to well above the break. Since $t_i \sim D_\ast \theta_*^2/2c$ and $D_\ast \approx R$, on average, $E_b \sim 1/\sqrt{t_i}$ for small $t_i$ and changes to $E_b \sim 1/t_i$ for large $t_i$. (For a GC with a uniform stellar distribution, the probability of $D_\ast$ is proportional to $D_\ast^2$ and consequently most of the stars have $D_\ast \approx R$.)

7. The relative arrival time at a star of atoms with a Lorentz factor $\Gamma$ is given by $t' \equiv t - t_i \approx D_\ast/2c\Gamma^{-2}$. Such atoms boost the star-light to an energy $\epsilon_\gamma \sim 2\epsilon_X\Gamma$. Therefore, the peak energy, $E_p \equiv max E^2(dn_\gamma/dE)$, decreases during a pulse approximately as

$$E_p \sim 1/(t' + \delta t_\ast)^\alpha ; 1/2 \leq \alpha \leq 1,$$

(15)

where $\delta t_\ast \sim 1-100 \text{ ms}$ is an added time broadening due to the finite time of the explosion and the finite size of the region around the star where the bulk of the photo excitation/decay takes place. $E_p$ is maximal right after the pulse begins and decreases monotonically afterwards while the photon flux, $dn_\gamma/dE$, peaks at a later time which depends on the distribution of Lorentz factors in the flow. Power-law spectra yield photon fluxes during pulses that, on average, are time-asymmetric (fast rise and a slower decay) with longer pulses being more asymmetric. Pulses are predicted to be narrower and their peak luminosities shifted closer to the beginning of the pulse when viewed in higher energy bands (larger Lorentz factors) as demonstrated in Fig. 3.

8. The durations of GRBs have a bimodal distribution which is a trivial consequence of their multipulse nature and the fact that, on average, $T_p \ll \Delta T$ independent of $\Gamma$: Multipulse GRBs have durations which are equal approximately to the sum of the time-spacing between their pulses. Consequently, $T \sim \Sigma \Delta T \gg T_p$. This produces a bimodal distribution which
peaks around $T_p \sim 0.3 \, ms$ for single pulse GRBs and around $T \sim 25 \, s$ for multipulse GRBs. This is demonstrated in fig. 4 for simulated explosions in a MW-like GC.

9. The photon column densities of MW-like GCs are not large enough to attenuate the relativistic flows. When a relativistic flow emerges from a GC it continues to boost star-light into gamma rays outside the GC and to emit synchrotron (radio) radiation when it traverses interstellar magnetic fields. The extended low level $\gamma$ ray emission, which includes much broadened and weaker stellar pulses, may last for hours. It is, however, below the current detection sensitivity of GRB detectors. The radio emission which lasts for thousands of years may be detectable [16].

10. The relativistic flows may also collide occasionally with interstellar gas (stellar winds, planetary nebulae, etc) or with a molecular cloud with a sizeable column density in/near the GC. Typical clouds, have $R \sim 5 \, pc$ and $M \sim 10^4 M_\odot$, yielding proton column densities of $N_p \sim 10^{22} cm^{-2}$. The total inelastic high energy cross section of iron nuclei on protons is $\sigma \approx 10^{-24} cm^{-2}$. Thus, nuclear collisions of the flow with a molecular cloud near the explosion will produce pions, and consequently, a burst of $\sim 10^{51} erg$ multi GeV $\gamma$ rays through $\pi^0 \rightarrow 2\gamma$ decays (and neutrinos through $\pi^\pm \rightarrow \mu \nu_\mu$ and $\mu \rightarrow e\nu_e\nu_\mu$ decays) with a power-law spectrum $dn_\gamma/dE \sim E^{-p}$. For $p \sim 2$, production of $\sim 20 \, GeV$ $\gamma$ rays comes from $\pi^0$'s produced mainly by nuclei with $\Gamma \sim 200$. Thus $\pi^0$ produced $\gamma$ rays of 20 GeV are delayed, typically, by $D/2c\Gamma^2 \sim 2h$, as was observed in the case of the 17 February 1994 GRB [20].

In conclusion, we have described a simple mechanism by which NS mergers/accretion induced collapse in dense galactic cores produce cosmological GRBs. The remarkable success of the model in reproducing all the main observed temporal and spectral properties of GRBs [16] strongly suggests that GRBs are $\gamma$ ray tomography pictures of dense cores of distant galaxies. The proposed mechanism may play an important role also in other astrophysical gamma ray sources such as AGN, pulsars and other cosmic accelerators.

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Figure 1: A schematic drawing illustrating the formation of a GRB by a highly relativistic spherical flow in a dense stellar region. Most of the observed $\gamma$ rays are produced by the radiative decay of photoexcited atoms near stars within a cone with an opening angle $\theta \sim 1/\Gamma$ along the direction to the observer.
Figure 2: (a) A light curve of a simulated GRB and its temporal power spectrum. The straight line represents the $w^{-2}$ power law dependence. (b) The light curve of GRB 920110 from the BATSE 1B catalog [18] and its temporal power spectrum.
Figure 3: A simulated GRB from a MW-like GC viewed in different energy bands.

Figure 4: The duration distribution of simulated GRBs from a MW-like GC [16].