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Origin of delayed GeV emission from gamma-ray bursts within stellar clusters

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A significant part of long Gamma-ray Bursts (GRBs) shows delayed hard GeV gamma-ray emission in addition to the dominant emission observed in the keV-MeV energy range. We argue that such emission can appear when the anisotropic explosion of a massive star occurs in a dense stellar cluster. Then, the delayed GeV gamma-rays can be produced when the hyper-relativistic jet encounters the radiation of stars, within the stellar cluster, which happens to be immersed in the jet. The hard X-ray to soft gamma-ray radiation from the jet, heats the surfaces of encountered stars to temperatures above those expected from nuclear burning. Then, relativistic electrons in the jet can efficiently Inverse Compton up-scatter stellar radiation to the GeV energies. We have performed numerical calculations of the gamma-ray spectra produced in the IC pair cascade initiated by relativistic electrons in a dense stellar radiation field. The gamma-ray spectra produced in such scenario form additional component in the GRB spectrum which is delayed in respect to the main emission, coming from the central part of the GRB engine, since stars can be encountered up to a parsec distance scale from the GRB. Such mechanism is discussed for the delayed GeV emission recently observed from the powerful GRB 130427A.

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1. Introduction

The high energy emission of some Gamma-ray Bursts (GRBs) is characterised by two components, the prompt one, in the keV-MeV energy range, and the delayed one, in the GeV energy range. For example, GRB 940217 showed delayed emission observed up to 90 min after the start of the afterglow phase with an 18 GeV photon detected after ∼75 min [1]. The *Fermi* Observatory confirmed that about ∼10% of GRBs emit delayed photons with energies above 100 MeV [2]. The highest energy delayed GeV photons, with energy 73 GeV and 95 GeV, has been observed in the case of the GRB 130427A at the redshift of 0.34 [3]. These two photons were delayed by $\tau_{\rm d} = 19\,$s and 244 s after the start of the burst. Its GeV emission has a flat spectrum with typical index of -2, consistent with the indices of other bursts. GeV emission is probably not produced in the synchrotron or the synchrotron Inverse Compton process. Instead, it is the result of comptonization of the external radiation field by electrons in the jet [3]. Up to now, no GRB has been detected at sub-TeV γ-ray energies by the Cherenkov telescopes [4, 5, 6].

It is commonly expected that long GRBs appear as a result of asymmetric explosions of massive stars, the so-called collapsar model [7, 8]. Such massive stars have to stay within dense, massive stellar clusters due to their relatively short evolutionary period. The Lorentz factors of GRB jets are usually constrained in the range ∼100-1000, in order to fulfil the opacity conditions for the observed MeV γ-rays. The mechanism for the delayed GeV emission is less obvious. This radiation has been proposed to come from the forward shock moving along the jet, which accelerates electrons and/or hadrons, see e.g. the review articles [9, 10, 11, 12].

In this paper we propose that the delayed GeV emission is produced by electrons in the jet which encounters soft radiation from the stars. The stars are irradiated by the hard X-ray emission from the GRB jet to temperatures that clearly overcome the stellar temperature expected from the nuclear burning. We note that huge number of stars in the stellar cluster is expected to surround the GRB source. Some of these stars can find themselves within the jet region, creating dense radiation field for the approaching hyper-relativistic jet containing relativistic electrons. We discuss such scenario in the context of the observations of GRB 130427A.

2. GRB within massive stellar cluster

Explosions of massive stars have to occur within massive stellar clusters containing of the order of hundred tausend stars in the region of a few pc. Such clusters have masses and densities typical for globular clusters but ages characteristic for open clusters, i.e. between a few 100 Myrs and a few Gyrs. Large population of such young and compact clusters in the nearby galaxies, with ages below 100 Myrs, masses above 10^6 M$_\odot$ and radii < 15 pc, has been found by using the Hubble Space Telescope (HST) [13, 14, 15, 16]. At farther distances, the proto-globular clusters are also observed, with the masses in the range $(1-20)\times 10^6$ M$_\odot$ [17]. Such young globular clusters can continuously form in the local universe as a result of galaxy mergers [18].

We consider a young stellar cluster with the mass of 10^6 M$_\odot$ and a typical radius of the order of $R_{\rm cl} = 1R_1$ pc. In order to estimate the number of stars with different masses within such young stellar cluster, we use the initial stellar mass function of stars, $dN/dM \propto M^{-\beta}$, with $\beta = 2.35$ above 0.5 M$_\odot$ [19, 20]. Below the mass 0.5 M$_\odot$, the mass function flattens ($\beta = 1.3$[20]). Then, the number of stars with the masses above 10 $M_\odot$, 3 $M_\odot$, and 1 $M_\odot$ can be estimated on $\sim 10^4$, $\sim 5\times10^4$, and $\sim 2\times10^5$, respectively.

A jet from the GRB source has to propagate through the cluster with the Lorentz factor $\gamma_{\rm j}$. The jet opening angle is estimated in the range of $\theta \sim 0.015-0.05$ rad, for typical values of the jet power $\sim10^{51}$ ergs and the break time $\sim 10^4-10^5$ s [9, 21]. This corresponds to the fraction of the sphere $\theta^2/2 \sim 10^{-4}-10^{-3}$. Simple estimate shows that up to hundreds of stars with masses above 1 $M_\odot$ can be immersed within the GRB jet on the distance of the order of parsecs. The star, which happens to stay within the hyper-relativistic jet of GRB, should suffer huge heating from a very powerful central engine and the jet. The effective temperature, T, reached by a part of the stellar surface exposed to the jet, can be estimated for the observed energy flux of the radiation in the GRB, $F_{\rm x}$, on $F_{\rm x}(D_{\rm L}/D_\star)^2 = \sigma_{\rm SB}T_{\rm eff}^4$, where $D_{\rm L}$ is the luminosity distance to this GRB, $D_\star = 0.1D_{0.1}$ pc is the distance of the star from the GRB engine, and $\sigma_{\rm SB}$ is the Stefan-Boltzmann constant. As an example, we approximate the energy flux from one of the most powerful burst recently observed, i.e. GRB 130427A ($D_{\rm L} = 1.8\,$Gpc, the redshift $z = 0.34$), based on the measurements of the GBM detector on board of the *Fermi* Observatory by [3], $F_{\rm x}({\rm erg\,cm^{-2}s^{-1}}) \sim 2\times10^{-5}$ for $t < 4.5\,$s, 6×10^{-4} for $4.5\,{\rm s} < t < 11.5\,$s, and $3\times10^{-6}(t/11.5\,{\rm s})^{-0.7}$ for $t > 11.5\,$s. If this energy flux overshines the star then, the effective temperature of the stellar surface can reach the value, $T(10^5K) \sim 1D_{0.1}^{-0.5}$ for t<4.5 s, $2.4D_{0.1}^{-0.5}$ for t<11.5 s, and $0.65D_{0.1}^{-0.5}(t/11.5\,{\rm s})^{-0.175}$ t>11.5 s. It is estimated assuming that the incident energy is immediately irradiated from the stellar surface. In reality this process will last for some time depending in details on the energy transfer processes in the stellar atmosphere. Therefore, the estimated temperatures should be considered as the upper limits. As a result of the irradiation by the hyper-relativistic jets of GRBs, stars within the distance scale of the order of a parsec can reach temperatures clearly larger than expected from their nuclear burning. Note that the binding energy of a star very close to the central engine of the GRB can be lower than the energy transferred from the GRB jet to the stellar surface, i.e. $E_{\rm b} = 3GM_\star^2/(5R_\star) \approx 2.3\times10^{48}M_\odot^2/R_\odot$ ergs is lower than $E_{\rm j}^\star = E_{j,iso}R_\star^2/(4\pi D^2) \approx 1.4\times10^{40}E_{54}R_\odot^2/D_{0.1}^2$ ergs, where $E_{j,iso} = 10^{54}E_{54}$ erg is the jet power re-calculated to the isotropic emission. We conclude that only stars at distances less than, $D \approx 2.3\times10^{13}R_\odot^{3/2}/M_\odot$ cm, can be completely disrupted by the GRB jet. The main sequence stars, i.e. the Solar type, O type or WR type, are very likely to survive the explosion of the GRB within stellar cluster provided that they are at distances from the central engine larger than $\sim2\times10^{14}$ cm. However, the evolved Solar mass stars in the red giant phase are expected to be disrupted at distances smaller than $\sim 4\times10^{16}$ cm. We propose that the radiation field from over-heated stars in the jet create additional target for relativistic electrons accelerated in the GRB jet. Then, the relativistic electrons in the jet find strong target for comptonization of the stellar radiation, producing delayed hard GeV γ-ray component observed from GRBs.

3. Delayed GeV gamma-ray emission in GRBs

We propose that GRBs with delayed GeV γ-ray emission appear within massive stellar clusters in which the number of stars, surrounding the progenitor of GRB, is of the order of 10^6. Then, some of those stars can find themselves within the region of the hyper-relativistic jet. Relativistic electrons in the jet can efficiently comptonize soft radiation from the star. The γ-ray photons with GeV energies are expected to be efficiently produced at a relatively long period after the initial

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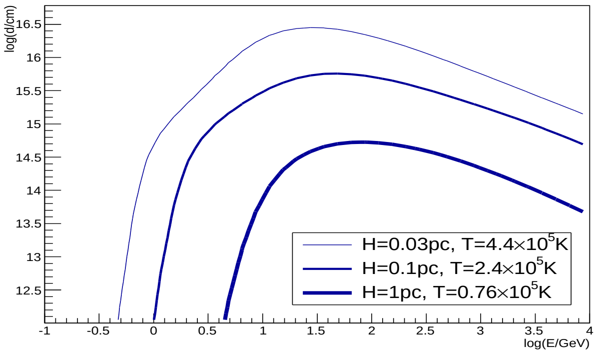

Figure 1: The impact parameter of the γ-ray photon (in respect to the location of the star) for which the optical depth in the radiation field of the O type star, with radius 10^{12} cm, is equal to unity. The star is located at different distances from the central engine of GRB: $H = 0.03$ pc (thin solid curve), 0.1 pc (middle curve), and 1 pc (thick). The distance, H, determines the surface temperature of the star (see main text for details).

collapse of the star as a result of the inverse Compton (IC) scattering of radiation of the encountered star. We calculate the γ-ray spectra expected in such process by modifying the numerical cascade code which follows the inverse Compton $e^\pm$ pair cascade initiated by relativistic electrons in the jet which encounter soft radiation from the star. The details of this code (developed originally for the AGN jets) can be found in [22]. The region around the star in which such IC $e^\pm$ pair cascade can develop depends on the γ-ray impact parameter, d, the distance of the star from the base of the jet, H, and the instantaneous luminosity of the central engine. This region can be much larger than the dimension of the star. For the stars at sub-parsec distances from the jet base, the temperature of the star, iluminated by the energy realised in GRB, can reach values significantly larger than those expected from the nuclear burning. In Fig. 1, we show for a few locations of the O type star, the distance of the impact parameters of γ-rays of a given energy, for which their optical depths at in the stellar radiation is equal to unity. We conclude that a single star can extract energy from leptons within the region which linear size is a hundred times larger than the radius of the O type star (assumed to be 10^{12} cm) for its location at the distance of 1 pc and up to ten tausend times larger for the distance of 0.03 pc.

We performed calculations of the γ-ray spectra from jets of GRBs in terms of such model. The jets of GRBs are characterised by Lorentz factors of the order of a few hundred. The spectrum of electrons in the rest frame of the jet plasma is assumed to be of the power law type and the spectral index close to -2 with the high energy cut-off at 10 GeV. Electrons are distributed isotropically in the jet reference frame. We assume cylindrical region in the jet with the radius corresponding to the jet perpendicular extend, i.e. $R_\mathrm{b} = \alpha_\mathrm{j} H$ and the height, H_b, not smaller than the dimension corresponding to the activity of the central engine revealed by the duration of the keV-MeV emission. In the case of already mentioned above GRB 130427A, this time scale is of the order of $\tau_\mathrm{keV-MeV} \sim 10$ s. Then, the height of the blob in the star reference frame is of the order of $H_\mathrm{b} \approx 2c\gamma_\mathrm{j}^2\tau_\mathrm{keV-MeV} \approx 5\times10^{16}\gamma_{300}^2$ cm, where the jet Lorentz factor is $\gamma_\mathrm{j} = 300\gamma_{300}$. **!!! w jakim ukladzie H_b? jak to wczesniej liczylismy to skalowanie bylo z γ^2, jezeli H w ukladzie gwiazdy !!!** The γ-ray spectra from the type of the cascade defined above are shown in Fig. 2 in the

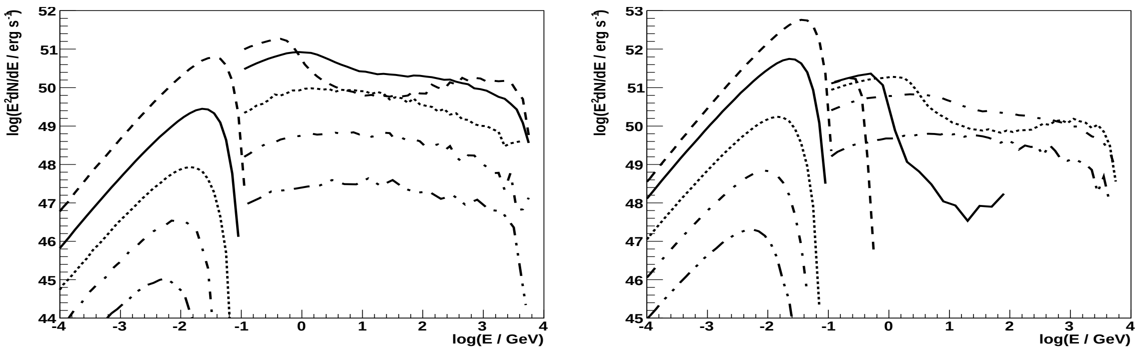

Figure 2: Spectral Energy Distribution (SED) from the GRB jet expected in the case of the injection of relativistic leptons in the jet with the power law spectrum (spectral index equal to -2 between 2 MeV and 10 GeV) which encounter the Solar type star ($R_\star = 7\times 10^{10}$ cm, on the left) and O type star ($R_\star = 10^{12}$ cm, on the right). The surface temperature of the star is determined by the energy absorbed from the GBR by the stellar surface. The Lorentz factor of the jet is assumed to be $\gamma_{\rm j} = 300$ and the jet opening angle is equal to $\theta = 1^{\rm o}$. The isotropic energy output of the jet is $E_{\rm iso} = 10^{53}$ erg s^{-1}, and the efficiency of energy conversion to relativistic electrons from the jet is equal $\eta = 10\%$. We assume that the whole jet cross section is filled with relativistic electrons. Specific spectra are calculated in the frame of reference of the source for different distances from the central engine and the temperatures of irradiated stars, $H = 10^{16}$ cm and $T_\star = 7.6\times 10^5$ K (dashed), 3×10^{16} cm and 4.4×10^5 K (solid), 10^{17} cm and 2.4×10^5 K (dotted), 3×10^{17} cm and 1.4×10^5 K (dot-dashed), 10^{18} cm and 7.6×10^4 K (dot-dot-dashed).

case of a single Solar type star (radius $R_\star = 7\times 10^{10}$ cm) and a single O type star ($R_\star = 10^{12}$ cm). These stars are immersed within the jet at different distances from its base. The jet Lorentz factor is assumed to be equal to $\gamma_{\rm b} = 300$. Note that the surface temperature of the star is determined by the energy output of the central engine provided that it is larger than the natural temperature of the star defined by the nuclear processes. This minimum temperature is assumed to be equal to 3×10^4 K for the O type star and 6×10^3 K for the Solar type star.

The main features of the γ-ray spectra depend on the type of the star and its distance from the central engine. In the case of stars with large dimensions (O type) and close to the engine, the γ-ray spectra cut-off at a relatively low energies, below $\sim$1 GeV (see Fig. 2), due to the strong cascading effects of γ-rays propagating with a small impact parameters in respect to the star. These small impact directions are due to a relatively small perpendicular extend of the inner jet. However, if the massive stars are at large distances from the engine or the stars are relatively small (a Solar type), then the spectra can extend to the TeV γ-rays. These maximum energies are limited only by the maximum energies of relativistic electrons in the jet. The softenning of the γ-ray spectra at sub-TeV energies is due to the Klein-Nishina effects. In the case of a single, low mass star, at large distance from the central engine, the γ-ray fluxes drop significantly since most of the electrons collide with the stellar radiation with large impact parameters.

The jet itself has so large Lorentz factor that the stellar radiation can be comptonized to γ-ray energy range by electrons which are at rest in the jet rest frame. The characteristic energies of γ-rays produced in such a bulk comptonization process can be estimated from $E_\gamma^{\rm bulk} = \varepsilon_\star \gamma_{\rm j}^2 \sim 2.3 T_5 \gamma_{300}^2$ MeV, where the characterisitic energy of stellar photons is $\varepsilon_\star = 3k_{\rm B}T_{\rm e} \sim 26 T_5$ eV. The ratio of the emissions from the bulk comptonization and from the comptonization by relativistic electrons in the jet depends on the composition of the jet, i.e whether it is dominated by $e^\pm$ pairs or it is charge neutral electron-proton beam. It depends also on the efficiency of electron acceleration in the jet. Typically, the acceleration efficiency of relativistic electrons, of the order of $\eta \sim 10\%$, is assumed. However, 90% of available energy is still kept in "cold" particles that are at rest in the jet frame. For the neutral electron-proton jets the initial power in cold electrons is determined by the ratio of electron to proton rest mass ($m_{\rm e}/m_{\rm p}$). However, since electrons are electrically coupled to protons the available energy buget is limitted by the energy in protons. On the other hand, in the case of pure $e^{\pm}$ pairs jets, the power in cold leptons dominates over the power in relativistic electrons by an order of magnitude. We calculate the γ-ray spectra from the bulk comptonization of stellar radiation in the case of neutral electron-proton jets for different distances of the star from the central engine (see lower energy spectra in Fig. 2). The spectra form a characteristic feature at low γ-ray energies in addition to the spectra produced by relativistic electrons with the power law spectrum. We propose that the relative strength of this emission feature in respect to the level of the higher energy emission can serve as an indication of the $e^{\pm}$ pair dominance of the GRB jets. The observation of such a feature will allow the measurement the content of jets in GRBs.

4. Hard GeV γ-ray emission from GRB 130427A

We propose that the model, discussed above, can be responsible for the appearance of the delayed GeV γ-ray emission recently observed from the exceptionally bright GRB 130427A. This hard GeV emission produces separate component in the spectrum, not correlated with emission at the lower energy range observed by *Fermi*-GBM [3]. In the case of GRB 130427A, the hard emission starts after the main burst lasting for several seconds and continues up to a few hours. The highest energy γ-rays, with 73 GeV (98 GeV in the GRB reference frame) and 95 GeV (128 GeV), has been detected at 19 s and 244 s after the beginning of the burst. In order to find out whether such energetic γ-rays can be produced in terms of proposed here scenario, we calculate the γ-ray spectra corresponding to the moments of observation of those two highest energy events. In order to estimate the Lorentz factor of the relativistic outflow, γ(t), at the moments of the first and second γ-ray, we use the Blandford & McKee model [23] for expansion of the relativistic blast wave, which gives the following prediction $\gamma_{\rm j}(t) = \gamma_{\rm j,0}(t/t_0)^{-3/8}$, where $t_0 = 19$s is the moment of detection of the first high energy γ-ray. At that moment, the Lorentz factor of the GRB jet has been constrained on $\gamma_{\rm j,0} \sim 500$ [3]. Then, the Doppler factor for the second most energetic γ-ray photon, at $t = 244$ s, should be correspondingly lower as expected from the above formula for the evolution of the jet Lorentz factor, i.e. of the order of $\gamma \approx 190$. The above formula, for the dependence of the Lorentz factor of the jet on time, allows also to estimate the distance of the supposed star from the central engine. Its radiation serves as a target for the relativistic electrons. Since the jet is deccelerating, the distance at the moment of emission can be estimated by integrating the formula $H = \int_0^{t_\gamma} 2c\gamma_{\rm j}(t)^2 dt$. In such model, these two highest energy γ-rays are supposed to be produced at the distance $H_{19s} \approx 1.1\times 10^{18}$ cm and $H_{244s} \approx 2.2\times 10^{18}$ cm. If the Doppler factor of the jet, at the moment of first high energy photon is equal to $D_\gamma = 300$ then, distances of these stars have to be $H_{19s} \approx 4\times 10^{17}$ cm and $H_{244s} \approx 8\times 10^{17}$ cm.

We have calculated the γ-ray spectra expected in discussed above model in both cases, i.e. produced by relativistic electrons accelerated in the jet and from the bulk comptonization by electrons which are at rest in the jet frame. The calculations are done for the moments of emission of these

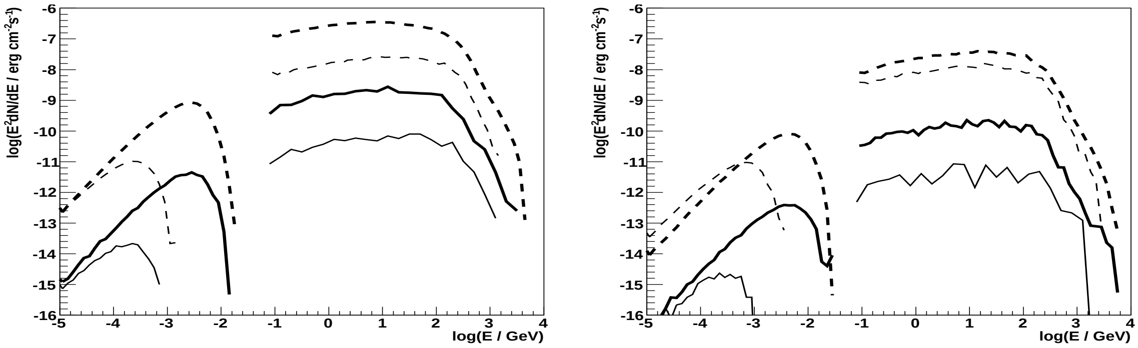

Figure 3: Spectral Energy Distribution (SED) of the γ-ray emission expected from the GRB 130427A at the moments where the two highest energy γ-ray events, 73 GeV (→98 GeV in GRB frame, thick curves) and 95 GeV (→128 GeV, thin curves), have been detected by the *Fermi*-LAT telescope, i.e. 19 s and 244 s after the GRB trigger. The spectra are calculated in the frame of the observer for the redshift of GRB 130427A z = 0.34 assuming two Doppler factors of the jets at the moment of first high energy event equal to 300 (on the left) and 500 (on the right). The Doppler factors of the jet at the moment of emission of the second γ-ray event is determined by the Blandford and McKee model (equal to 115 and 192, respectively). Relativistic leptons, injected with the power law spectrum and spectral index -2, in the jet interact with the Solar type star (solid curves) or with the O type star (dashed curves). The distance, H, of the star from the central engine is determined in Sect. 4 and the surface temperature of the star, irradiated by the GRB, is determined in Sect. 2. The effect of the propagation in the EBL is included [24]. The jet opening angle is assumed to be equal to 1°.

two highest energy γ-rays applying two different values for the Lorentz factor of the GRB jet (see Fig. 3). Moreover, the cases of the O type star and the Solar type star are considerred. In fact, for the spectral index of the electrons equal to -2, the γ-ray spectra peak at $\sim$100 GeV. Therefore, the appearance of such energetic γ-rays, long after the initail GRB flash, can be explained in terms of a star in jet scenario. Moreover, the GeV γ-ray flux observed during the periods around the moments of both high energy events, in the case of irradiation of the O type star, are generally consistent with the predictions of our model (see Fig. 3 and Fig. S1 in [3]). Note, that comptonization of the radiation of Solar type star is much less efficient in respect to the case of the O type star. This is due to a relatively small region in which the radiation field of such low radius star is dominant. As a consequence, only electrons within a part of the jet, which is close to the star, lose efficiently their energy on the ICS (see Fig. 1). On the other hand, the number of Solar type stars within the GRB jet can be substantial, providing a target for a more efficient extraction of energy from relativistic electrons.

5. Conclusion

Long GRBs, produced in explosions of massive stars, are expected to occur within massive stellar clusters. We propose that some of the cluster stars can be immersed within the powerful GRB jet, produced by the central engine, propagating with the Doppler factor of the order of a hew hundred. Then, relativistic electrons should comptonize soft radiation emitted by the star which is irradiated by the jet. We perform numerical calculations of the IC $e^{\pm}$ pair cascade initiated by these electrons in the stellar radiation. It is shown that the delayed hard GeV γ-ray component observed from substantial population of the long GRBs can be produced in such a scenario. We also calculate the lower energy γ-ray spectra produced by the electrons which are at rest in respect to the jet plasma. They also comptonize stellar radiation in the so called bulk comptonization process. As an example, we show the γ-ray spectra expected from the interaction of the jet in GRB 130427A with the O type star and the Solar type star at the moment of emission of the two highest energy γ-ray photons (98 GeV and 128 GeV in the source frame). In fact, such delayed GeV γ-ray emission might be also produced in the case of short GRBs as a result of the interaction of relativistic electrons with radiation from Solar type stars irradiated by GRBs occuring within massive globular clusters.

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