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Constraints on jet contents derived from multimessenger studies of gamma-ray bursts

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We are studying the constraints placed on the jet of gamma-ray bursts by the association of a high energy cosmic ray detection and the historical GRB 980425. Using the properties of this burst, we define a set of similar events, which statistically could produce similar UHECRs. From statistical studies on that sample, we show that the jet of GRBs should be extremely baryon-poor, if we want to account for the observed detection rate of UHECRs on Earth. This leads us to hypothesize that GRB jets are not accelerating the progenitor remnant but rather its surrounding medium.

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1. Introduction

Ultra-High Energy Cosmic Rays (UHECRs) are the most extreme particles in the Universe whose kinetic energies exceed 10^{18} eV. To date, their origins remain a mystery despite a range of sources being suitable candidates due to their proximity, energy budget, and number density (see [1] for a review). Among these candidates are Gamma-Ray Bursts (GRBs) - the most powerful and luminous extra-galactic transients in the Universe with energies ranging from $10^{49} - 10^{53}$ erg [2, 3]. The fireball model [4–6] is the leading model to describe GRB emission, in which a central engine injects relativistic shells of plasma within a jet that collide, producing the gamma-rays observed in the prompt emission. It is these shell collisions that provide an ideal site for particle acceleration via the Fermi mechanism [7, 8].

There has been a recent tentative association between a high energy photon due to UHECR interactions and GRB980425 [9, 10], which has reinvigorated interest regarding the possibility that some UHECRs are produced by GRBs. GRB980425 is the closest GRB to date [11], and resides within the the Greisen-Zatsepin-Kuzmin (GZK) horizon [12, 13]. These two facts prove that such bursts are promising UHECR source candidates. GRB980425 is a member of the low-luminosity GRB (LLGRB) class population, and the suitability as UHECR sources of this population has been theoretically explored by, e.g. [14–20]. It is thus logical to use a statistically significant sample to compute their occurrence rate in the Universe, and compare it with the observed rate of UHECRs. This has been done in [21] (submitted), and this proceeding summarises and expands on the results.

2. Data

For our calculations, we consider a sample of GRBs that are similar to GRB980425 taken from [22], which is the most recent complete sample of LLGRBs. These bursts were selected by their X-ray properties which act as a proxy for the total fireball energy measurement. We list the sample of 41 GRBs in Table 1 along with some of their properties. This sample consists of events detected between 1998 and 2016 mostly from the Neil Gehrels Swift Observatory (38 bursts out of 41). Since even three bursts detected by other instruments (BeppoSAX, 2 bursts, and INTEGRAL, 1 burst) could introduce a bias due to their different sizes of their field of view, we deconvolve this bias by correcting each computed rate for the size of the field of view, assuming that GRBs are isotropically distributed [23]. We list in Table 2 the effective time span for each instrument and the field of view of its detector.

Additionally, for the particle component of our analysis, in this work we use the flux of UHECR baryons above 10^{19} eV detected by Pierre Auger [24] of 1 particle km^{-2} yr^{-1}, which we do not correct for any effects.

3. Results

Our method of calculating the expected rate of LLGRBs in the local Universe is explained in [21] (submitted), and can be summarised as follows:

$$F_{\text{particle}} = \frac{4\pi \times N \times (d_{\text{GZK}})^3 \times R_{\text{tot}} \times f_b}{3 S_{\text{GZK}}}. \tag{1}$$

GRB	$E_{\rm iso}$ [10^{52} erg]	z	Rate [Mpc^{-3} yr^{-1}]
GRB980425	$(1.3 \pm 0.2) \times 10^{-4}$	0.0085	6.418×10^{-7}
GRB011121	7.97 ± 2.2	0.36	1.104×10^{-11}
GRB031203	$(8.2 \pm 3.5) \times 10^{-3}$	0.105	1.147×10^{-7}
GRB050126	$[0.4 - 3.5]$	1.29	2.664×10^{-12}
GRB050223	$(8.8 \pm 4.4) \times 10^{-3}$	0.5915	1.575×10^{-11}
GRB050525A	2.3 ± 0.5	0.606	1.482×10^{-11}
GRB050801	$[0.27 - 0.74]$	1.38	2.330×10^{-12}
GRB050826	$[0.023 - 0.249]$	0.297	9.790×10^{-11}
GRB051006	$[0.9 - 4.3]$	1.059	4.018×10^{-12}
GRB051109B	–	0.08	4.243×10^{-9}
GRB051117B	$[0.034 - 0.044]$	0.481	2.674×10^{-11}
GRB060218	$(5.4 \pm 0.54) \times 10^{-3}$	0.0331	5.790×10^{-8}
GRB060505	$(3.9 \pm 0.9) \times 10^{-3}$	0.089	3.102×10^{-9}
GRB060614	0.22 ± 0.09	0.125	1.150×10^{-9}
GRB060912A	$[0.80 - 1.42]$	0.937	5.259×10^{-12}
GRB061021	–	0.3463	6.424×10^{-11}
GRB061110A	$[0.35 - 0.97]$	0.758	8.583×10^{-12}
GRB070419A	$[0.20 - 0.87]$	0.97	4.868×10^{-12}
GRB071112C	–	0.823	7.073×10^{-12}
GRB081007	0.18 ± 0.02	0.5295	2.086×10^{-11}
GRB090417B	$[0.17 - 0.35]$	0.345	6.490×10^{-11}
GRB090814A	$[0.21 - 0.58]$	0.696	1.054×10^{-11}
GRB100316D	$(6.9 \pm 1.7) \times 10^{-3}$	0.059	1.042×10^{-8}
GRB100418A	$[0.06 - 0.15]$	0.6235	1.380×10^{-11}
GRB101225A	$[0.68 - 1.2]$	0.847	6.617×10^{-12}
GRB110106B	0.73 ± 0.07	0.618	1.411×10^{-11}
GRB120422A	$[0.016 - 0.032]$	0.283	1.119×10^{-10}
GRB120714B	0.08 ± 0.02	0.3984	4.400×10^{-11}
GRB120722A	$[0.51 - 1.22]$	0.9586	4.998×10^{-12}
GRB120729A	$[0.80 - 2.0]$	0.8	7.557×10^{-12}
GRB130511A	–	1.3033	2.609×10^{-12}
GRB130831A	1.16 ± 0.12	0.4791	2.702×10^{-11}
GRB140318A	–	1.02	4.358×10^{-12}
GRB140710A	–	0.558	1.825×10^{-11}
GRB150727A	–	0.313	8.471×10^{-11}
GRB150821A	15.37 ± 3.86	0.755	8.664×10^{-12}
GRB151029A	0.44 ± 0.08	1.423	2.195×10^{-12}
GRB151031A	–	1.167	3.270×10^{-12}
GRB160117B	–	0.87	6.222×10^{-12}
GRB160425A	–	0.555	1.850×10^{-11}
GRB161129A	1.3 ± 0.2	0.645	1.269×10^{-11}

Table 1: Sample of 41 long GRBs from [22]. For each of them, we indicate their basic properties, and the rate we calculated following the method outlined in Section 3.

Instrument	FOV [sr]	Operation period [yr]	Considered years of operation
BeppoSAX	4π	7	1996–2002
Integral	0.02	14	2002–2016
Swift	1.4	12	2004–2016

Table 2: Summary of instruments used to detect GRBs in our sample.

In this equation, R_{tot} is the sum of the individual rates of each LLGRBs listed in Table 1. We restrict ourselves to events occurring within the GZK sphere ($d_{\mathrm{GZK}} = 50$ Mpc), under the assumption that they each produce N particles and are beamed by an unknown beaming angle, which induces a beaming factor correction f_b. The true value of this beaming factor lies between the two extremes $f_b \in [1, S_{\mathrm{GZK}}/S_{\mathrm{Earth}}]$.

Therefore, the UHECR flux from LLGRBs lies between $N \times 8.8 \times 10^{-21}$ particles km^{-2} yr^{-1} and $N \times 5.2 \times 10^{14}$ particles km^{-2} yr^{-1} if N is expressed in mols, which needs to be compared to the observed value of 1. This leads to the final result that, in order to reconcile both numbers, N has to be located between 10^{-47} and 10^{-13} $\mathrm{M}_{\odot}$, assuming 1 $\mathrm{M}_{\odot} \sim 10^{33}$ mol of baryons.

4. Discussion

Albeit not being "normal" long GRBs, low-luminosity GRBs are still long events with the progenitor expected to be a collapsar, i.e. a massive star [25]. In this model, part of the stellar progenitor forms a stellar-mass black hole, with some unknown fraction of the star accreted onto the compact object, and the remaining being expelled from the system. One could then think that the jet producing the GRB could be contaminated by some of the stellar material. We can incidentally note that this contamination (increasing the baryon load of the jet) was one possible explanation of the nature of low-luminosity GRBs (e.g. [26]).

Intuitively, the number 10^{-13} $\mathrm{M}_{\odot}$ (which is an upper limit here) is not well-aligned with a massive stellar progenitor. When considering the energy budget of GRBs, we typically see $E \sim 10^{54}$ erg, which corresponds to about 1 $\mathrm{M}_{\odot}$ of accreted material. Even if one assumes half of the progenitor mass is transferred into the newly formed black hole, this leaves several solar masses available for acceleration, and thus for being turned into UHECRs. If one wishes to reconcile these numbers, then a suppression mechanism has to play a major role into the acceleration of UHECRs by GRBs.

A first solution would be to break the isotropic distribution hypothesis. It is well known that magnetic fields in the Universe (i.e. the Galactic and Intergalactic Magnetic Fields, GMF and IGMF respectively) impact the trajectory and arrival time of UHECR particles. Our understanding of the GMF has been refined in recent years (e.g. [27, 28]), and it may appear on the surface that it may indeed pose a break in the isotropy hypothesis of the Λ-CDM model. However, as discussed in [29], magnetic fields cannot introduce anisotropies. As GRBs are indeed isotropically distributed in the sky [23], the resulting distribution of UHECRs sources due to GRBs will also be isotropic. This is also confirmed by the fact that there is no observational signature of the GMF dipole in cosmic ray arrival directions [30].

An alternative suppression mechanism is the interaction between UHECRs and the cosmic microwave background photons when traveling through space - the GZK effect. In our calculations, we have supposed that there were no interactions occurring within the GZK sphere, and that no UHECRs could reach us if the source was located outside the sphere. While the latter hypothesis is expected to be true [12, 13], the former may not be accurate. It would, in any case, be surprising that interactions within the GZK sphere are able to remove such a large fraction of baryons. This would mean that the difference between the inner part and the outer part of the sphere would then be negligible. However, this is not our preferred solution.

A second solution would be that our rate estimate is not correct, and that local GRBs are far rarer than what we estimated. In such a case the baryonic load of the jets would increase drastically, maybe up to the level of being compatible with the acceleration of the stellar content of the progenitor. However, a low baryonic load of the jet is in accordance with observations from neutrino detectors. So far, there has been no statistically significant association between both current and historical neutrino events and GRBs [31–34]. One would expect a neutrino flux from GRBs due to photohadronic interactions within the jet, given non-negligible baryonic loads are present (e.g. [35, 36]). The neutrino non-detection from GRBs may indeed be due to limitations in the sensitivity of current neutrino detectors, but on the other hand, it may also signify that the jet contents is more leptonic than hadronic in nature.

This leaves us with a last and far more straightforward solution: that the accelerated material is not provided by the stellar progenitor, but rather by its surrounding environment.

If one assumes the standard fireball model and the canonical values for its main parameters (a density of about 1 proton per cubic centimeter, a deceleration radius of 10^9 km, and a beaming angle of 15°), then the volume of the cone of matter that will be swiped forward by the jet contains about 10^{-18} $M_{\odot}$. This number is totally compatible with our calculation without the need of any extra hypotheses about propagation losses. The amount of matter is also low enough not to significantly impact the jet, which is a key condition for producing a GRB. Moreover, this acceleration is an expected effect of the propagation of the GRB jet within the surrounding medium, and the cause of the presence of an afterglow.

5. Conclusion

In this study we studied how efficient gamma-ray bursts are in producing ultra-high energy cosmic rays, and we found these events extremely efficient at producing them. In order to reconcile the expected production rate and the observed emission rate, we had to infer that if the acceleration site of UHECR for GRB is indeed the jet, the accelerated material should not be the stellar content but rather the surrounding material. In order to confirm this result, more detailed studies into the propagation losses of UHECRs within the GZK sphere are required. However, this could potentially have strong implications as it may impact the interpretation of the mass spectrum of the most energetic cosmic rays: are these particles representative of the content of an evolved massive star, or of the content of clouds of matter in distant galaxies?

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