Toward a robust inference method for the likelihood of low-luminosity gamma-ray bursts to be progenitors of ultrahigh-energy cosmic rays correlating with starburst galaxies

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Very recently, the Pierre Auger Collaboration reported a 4.5σ correlation between the arrival directions of the highest energy cosmic rays and nearby starburst galaxies. The cosmic rays producing the anisotropy signal have been proposed to originate in low-luminosity gamma-ray bursts (llGRBs). On the basis of the well-justified assumption that at redshift \( z < 0.3 \) the host metallicity is a good indicator of the llGRB production rate, we show that the association of llGRBs and the starbursts correlating with Auger data is excluded at the 90% confidence level.

I. GENERAL IDEA

By now, it is well-established that galactic-scale outflows of gas (generally called starburst-driven superwinds) are ubiquitous in galaxies in which the global star-formation rate per unit area exceeds roughly \( 10^{-1} M_\odot \text{yr}^{-1} \text{kpc}^{-2} \) [1]. These flows are complex, multiphase phenomena powered primarily by massive star winds and by core collapse supernovae (SNe), which collectively create hot (\( T \lesssim 10^8 \) K) bubbles of metal-enriched plasma within the star forming regions. The over-pressured bubbles expand at high-velocity sweeping up cooler ambient gas and eventually blow out of the disk into the halo. Starburst superwinds then provide a commonplace for the formation of collisionless plasma shock waves in which charged particles can be accelerated by bouncing back and forth across the shock up to ultrahigh energies [2]. Experimental data support this prediction: the Pierre Auger Collaboration reported a 4.5σ significance correlation between the arrival direction of cosmic rays with energy above 38 EeV and \( \sigma \) signifcance correlation between the arrival direction of cosmic rays with energy above 38 EeV and nearby starburst galaxies [3]. In the best-fit model, 11±5% of the cosmic-ray flux originates from these objects and undergoes angular diffusion on a scale \( \delta \sim 15^\circ - 15^\circ \). The latter angular spread derives from a Fisher-Von Mises distribution, the equivalent of a Gaussian on the sphere, and would correspond to a top-hat scale \( \varphi \sim 1.59 \times 8 \). Of course, readjustment of superwind-free-parameters are necessary to accomodate Auger data [5,7].

However, it was recently put forward the idea that ultrahigh-energy-cosmic-ray (UHECR) acceleration in low-luminosity gamma-ray bursts (llGRBs) could be the origin of the fraction of Auger events which correlates with starburst galaxies [8]. In this work we show that the association of llGRBs with the starbursts generating the anisotropy signal found in Auger data is disfavored by observation. Before proceeding, we pause to note that whether llGRBs would satisfy the power requirements to accelerate cosmic rays up to the highest observed energies may be up for debate [9,11].

The layout of the paper is as follows: in Sec. II we discuss the sample of llGRBs and starburst galaxies we have selected to study and conduct the statistical analysis; in Sec. III we draw our conclusions.

II. DATA ANALYSIS

We begin our study with an overview of the basic properties of the various GRB populations. A detailed scrutiny of the BATSE catalog led to our current duration-based classification system for GRBs: short GRBs (SGRBs) have burst durations of \(< 2 \) s, whereas long GRBs (LGRBs) have burst durations of \( > 2 \) s [12]. GRBs can also be split into according to their luminosities into llGRBs (\( L_{iso} < 10^{49} \) erg/s) and high-luminosity GRBs (\( L_{iso} > 10^{49} \text{erg/s} \)) [13]. Herein, we also adopt the conventions of [14] to identify nearby (\( z < 0.3 \)) GRBs from those at intermediate redshift (0.3 \( < z < 1 \)). We note, however, that recent studies do not show a strong evidence suggesting that \( z < 0.3 \) GRBs would be, as a population, different from the high-redshift one. Nevertheless, although one can find many high-luminosity GRBs at \( z < 0.3 \), the llGRBs at \( z > 0.3 \) cannot be detected due to the sensitivity of the gamma-ray detectors; see e.g. Fig. 1 in [15]. This last argument further justifies our redshift selection criterion.

Over the last two decades a consensus formed that LGRBs are a product of a core-collapse of a massive star [16] and that SGRBs have a different origin. Indeed, observations have proved the SNe type Ic-BL \( \approx \) LGRBs connection beyond any reasonable doubt [17,19]. Type Ic are core-collapse stripped-envelope SNe, whose progenitor stars have lost most of the hydrogen and helium in their outer envelopes prior to the collapse. Some SNe type Ic are found to have very broad lines in their spectra (type Ic-BL), indicative of very fast ejecta velocities.

Because GRBs are outlying and arise in small galaxies seldom monitored by high-angular resolution surveys, it has not been and will likely not be possible in the near future to image the progenitor of a GRB, thus we are only
able to figure out properties of the progenitor star from its environment. There are several studies that seem to indicate that GRB formation efficiency drops at high metallicity. For example, the host galaxies of five nearby LGRBs (980425, 020903, 030329, 031203 and 060218, each of which had a well-documented associated SN) are all faint and metal-poor compared to the population of local star-forming galaxies [20]. Moreover, various analyses of GRB host morphologies suggest a correlation between metallicity and LGRB occurrence rate; see e.g. [21-22].

In addition, a systematic comparison of the host galaxies of broad-lined SNe Ic with and without a detected GRB, indicates that a larger fraction of super-solar metallicity hosts are found among the SNe Ic-BL without a GRB [23]. Models of stellar evolution further reinforce the metallicity bias for LGRB progenitors. This is because the well-established correlation between LGRB and stripped-envelope SNe points to carbon- and oxygen- rich Wolf-Rayet (WR) stars as the most promising progenitor candidates [24-25]. WR stars emit winds that eject about 10\( M_\odot \) of material per million years at speeds of up to 3,000 km/s, resulting in the characteristic broad emission lines in the spectra of these stars (normal stars have narrow emission lines). It is thought that these powerful winds are driven by intense radiation pressure on spectral lines, yielding a dependence of the wind-driven mass loss rate on surface metallicity [26-27]. Thereupon, the surface rotation velocities of WR stars are expected to decrease at higher stellar metallicities because of the higher mass loss rates [28]. For WR stars, the metallicities characterizing their host environments can be adopted as the natal metallicities of the stars themselves. This entails that the higher wind-driven mass loss rates in metal-rich environments would remove from the massive WR stars too much angular momentum, inhibiting them from rotating rapidly enough to produce a LGRB [24-29]. All in all, the data seem to indicate that LGRBs should be confined to low-metallicity environments.

Though a priori there is no reason to assume that LGRBs and llGRBs are related, the similarity of their associated SNe implies that llGRBs and LGRBs have similar progenitors and similar inner explosion mechanisms [30]. In light of the preceding discussion, it seems reasonable to assume that the metallicity of the host environment would also be a good discriminator of llGRB progenitors. In what follows we compare the host metallicity of llGRBs with that of the starbursts dominating the signal in Auger data.

Before we can conduct the statistical analysis, we need to define our samples. The Auger anisotropy search included a sample of 23 starburst galaxies with a flux larger than 0.3 Jy selected out of the 63 objects within 250 Mpc search for \( \gamma \)-ray emission by the Fermi-LAT Collaboration [31]. This selection was updated in [4] with the addition of the Circinus Galaxy and sources selected from the HEASARC Radio Master Catalog [2]. The number of starbursts selected this way is 32. Here we consider 10 of these galaxies (including all sources dominating the Auger anisotropy signal) for which the average metallicity has been determined. It is important to note that some galaxies in the starburst sample have a double starburst/AGN nature (e.g., Circinus, NGC 4945, NGC 1068). Given that so far, despite efforts, no GRB host galaxy has been found to host an AGN, it may not come as surprising if the two samples are not drawn from the same underlying probability distribution. We consider all llGRB detected at \( z < 0.3 \). The metallicities of llGRB hosts are given in Table I and the metallicities of the starbursts are given in Table II. Following [47], we have taken \( \log(Z/Z_\odot) = \log(O/H) - \log(O/H)_\odot \), with

\[\text{TABLE I: Properties of nearby llGRBs.}\]

| GRB ID  | \( \log(L_{\gamma}/(\text{erg/s}) \) | Redshift | \( 12 + \log(O/H) \) | References |
|---------|---------------------------------|----------|----------------|-------------|
| 980425  | 46.67                           | 0.008    | 8.3            | [14, 20, 32] |
| 020903  | 48.92                           | 0.251    | 8.0            | [14, 32, 33] |
| 031203  | 48.55                           | 0.105    | 8.1            | [14, 32, 33] |
| 051109B | 48.22                           | 0.080    | \cdots         | [34]        |
| 060218  | 46.78                           | 0.033    | 8.1            | [14, 32, 33] |
| 060505  | 48.85                           | 0.089    | 8.4            | [33, 35]    |
| 080517  | 48.52                           | 0.089    | 8.6            | [35, 39]    |
| 100316D | 47.75                           | 0.059    | 8.2            | [33, 40, 41]|
| 111005A | 46.78                           | 0.013    | 8.6            | [36, 42, 43]|
| 171205A | 47.50                           | 0.037    | 8.4            | [44, 45]    |

\[\text{TABLE II: Properties of nearby starburst galaxies.}\]

| Starburst ID | Distance (Mpc) | \( 12 + \log(O/H) \) | References |
|--------------|----------------|----------------------|-------------|
| NGC 253      | 2.7            | 8.7                  | [3, 45, 46] |
| M82          | 3.6            | 8.8                  | [3, 47]     |
| NGC 4945     | 4.0            | 8.5                  | [3, 48]     |
| M83          | 4.0            | 8.8                  | [3, 45, 46] |
| IC 342       | 4.0            | 8.8                  | [3, 46, 49] |
| Circinus     | 4.0            | 8.4                  | [50]        |
| NGC 6946     | 5.9            | 8.8                  | [3, 45, 46] |
| M51          | 10.3           | 8.8                  | [3, 45, 46] |
| NGC 891      | 11.0           | 8.7                  | [3, 51, 52] |
| NGC 1068     | 17.9           | 8.8                  | [3, 45, 46] |

\[\text{\textsuperscript{a}An estimate of the GRB 171205A host metallicity is given in the journal (but not in the arXiv) version of [44].}\]

\[\text{\textsuperscript{b}See, in particular, Table A.1 of [47].}\]

\[\text{\textsuperscript{c}See, in particular, Table 1 of [50].}\]

\[1\] WR stars are highly luminous massive objects which are at an advanced stage of stellar evolution and losing mass at a very high rate.

\[2\] \url{https://heasarc.nasa.gov/W3Browse/master-catalog/radio.html}
12 + log(O/H)⊙ = 8.69 and Z⊙ = 0.019 being the solar values \(^{[53]}\).

Before proceeding, some technical remarks are in order to clarify our metallicity selection criteria. Molecular gas in starbursts exists under conditions very different from those found in most normal galaxies. Observations of starbursts suggest widespread gas volume and column densities much higher than those typical of normal disks \(^{[55, 56]}\). The nebular oxygen abundance is the canonical choice of metallicity indicator for studies of the interstellar medium since oxygen is the most abundant metal, only weakly depleted, and exhibits very strong nebular emission lines in the optical wavelength range \(^{[57]}\). Extensive analyses have been carried out to calibrate metallicity studies by using only strong emission lines. One of the most frequently used metallicity diagnostics is the parameter

\[
R_{23} = \log_{10} \left( \frac{[\text{O}III] \lambda 3727 + [\text{O}II] \lambda 4959, 5007}{\text{H} \beta} \right),
\]

defined as the ratio of the flux in the strong optical oxygen lines to that of H\( \beta \) \(^{[58]}\); notation conventions are those in \(^{[59]}\). However, a well-known problem of this metallicity diagnostic is that the \( R_{23} \) vs. 12 + log(O/H) relation is double-valued, and so additional information is required to break this degeneracy. Several methods have been developed to remove the \( R_{23} \) degeneracy exploiting the [NII], [SII], and H\( \alpha \) lines; e.g.,

\[
N2 = \log_{10} \left( \frac{[\text{N}II] \lambda 6584}{\text{H} \alpha} \right),
\]

\[
O3N2 = \log_{10} \left( \frac{([\text{O}III] \lambda 5007) + [\text{N}II] \lambda 6584}{(\text{H} \alpha/\text{H} \beta)} \right),
\]

\[
y = \log_{10} \left( \frac{[\text{N}II] \lambda 6584}{[\text{S}II] \lambda 6717, 6731} \right) + 0.264 \log_{10} \left( \frac{[\text{N}II] \lambda 6584}{\text{H} \alpha} \right),
\]

proposed in \(^{[60, 61]}\) and \(^{[62]}\). Although an absolute calibration for metallicities obtained through the strong-line methods remains uncertain \(^{[63]}\), we may still use the strong-line ratios to study the trend in metallicities between the IGRB hosts and starburst galaxies in our sample. Indeed, the absolute metallicity scale varies up to \( \Delta \log(O/H) \approx 0.7 \), depending on the calibration used, and the change in shape is substantial. It is critical then to use the same metallicity calibration when comparing different metallicity relations. Herein we adopt the \( O3N2 \) diagnostic with normalization as given in \(^{[61]}\),

\[
12 + \log(O/H) = 8.73 - 0.32 \times O3N2,
\]

and use the metallicity conversions given in \(^{[63]}\), which allow metallicities that have been derived using different strong-line calibrations to be converted to the same base calibration. In TablesI and II we provide the best-fit values of the metallicities after conversion to the same base calibration. Following \(^{[52]}\), an uncertainty of 0.1 dex in the O/H number abundance accounts for the typical dispersion between independent measurements. To remain conservative, in our calculations we adopt the upper and lower end of the 1σ metallicity range to characterize the IGRB and starburst samples, respectively. Concerning GRB 051109B, it has been tentatively associated with a star-forming region in a spiral galaxy which lacks of any strong emission features \(^{[64]}\). Therefore, we do not include this event in our statistical analysis.

Next, we adopt the Kolmogorov-Smirnov (two-sample) test to check whether the two data sets of metallicity are both drawn from the same underlying probability distribution, but without assuming any specific model for that distribution \(^{[65, 66]}\). The calculations that are involved in application of the Kolmogorov-Smirnov test are quite simple. We begin by stating the null hypothesis \( \mathcal{H}_0 \): if \( f_m(x) \) and \( g_m(x) \) are samples of two underlying probability density functions \( f(x) \) and \( g(x) \), then

\[
\mathcal{H}_0 : f(x) = g(x), \forall x.
\]

The alternate hypothesis is that \( f(x) \neq g(x) \). Now, given any sample from an unspecified population, a natural estimate of the unknown cumulative distribution function of the population is the empirical (or sample) distribution function (EDF) of the sample, defined, at any real number \( x \), as the proportion of sample observations which do not exceed \( x \). For a sample of size \( m \), the empirical distribution function will be denoted by \( F_m(x) \) and may be defined in terms of the order statistics \( X_{(1)} \leq X_{(2)} \leq \cdots \leq X_{(m)} \) by

\[
F_m(x) = \begin{cases} 
0 & \text{if } x < X_{(1)} \\
j/m & \text{if } X_{(1)} \leq x \leq X_{(j+1)}, \quad 1 \leq j \leq m \\
1 & \text{if } x \geq X_{(m)} 
\end{cases},
\]

i.e., \( F_m(x) \) is the staircase function.

To form the test statistics \( D \) from the sample distribution functions \( F_m(x) \) and \( G_m(x) \) we compute their maxi-
We may reject the null hypothesis of the maximum absolute difference over all the values of \( x \),

\[
D = \max_x |F_m(x) - G_n(x)| .
\] (6)

Graphically, we may interpret this as the maximum vertical displacement between the two sample distribution functions as indicated in Fig. 4.

Testing of the null hypothesis proceeds by comparison of \( D \) against critical values \( D_\alpha \) which are functions of the confidence level \( \alpha \) and the sizes of the samples \( m, n \) [67]. We may reject the null hypothesis \( H_0 \) at the \((1 - \alpha)\) confidence level if \( D > D_\alpha \). For the case at hand, \( m = 9 \) and \( n = 10 \), the upper critical value of the 90\% confidence level interval is \( D_{0.1} = 5/9 \) [68]. Since the maximum difference between the EDFs shown in Fig. 1 is \( D = 26/45 \), we infer that the null-hypothesis (the two metallicity samples belong to the same distribution) is excluded at the 90\% confidence level. Therefore, on the basis of the well-justified assumption that at redshift \( z < 0.3 \) the host metallicity is a good indicator of the llGRB production rate, we can conclude that the association of llGRBs and the starbursts correlating with Auger data is disfavored by observation.

### III. CONCLUSION

We have used the metallicity of the llGRB host galaxies as a proxy to investigate whether llGRBs can be the sources of the highest energy cosmic rays whose arrival directions correlate with the celestial positions of nearby starburst galaxies. We have shown that the association of llGRBs and the starbursts correlating with Auger data is excluded at the 90\% confidence level. We end with two observations:

- The first one builds upon the estimates in [69] and contributes to the debate on the power requirements. The Telescope Array Collaboration has reported an excess of UHECR events over expectations from a random distribution in a circle of 20\° near M82 [70]. The hotspot energy flux in UHECRs with energies \( E > E_0 = 5.7 \times 10^{10} \) GeV is estimated to be

\[
F_{hs} = \Omega_{20\°} \int_{E_0}^{\infty} E f_{hs}(E) dE = 1.7 \times 10^{-8} \xi_{1.7} \text{ (GeV cm}^2 \text{ s)}^{-1} ,
\] (7)

where \( \Omega_{20\°} \approx 0.38 \) is the hot-spot solid angle and \( \xi_{1.7} \) parametrizes the uncertainty in the energy dependence of the specific (number) intensity in the hotspot \( f_{hs}(E) \) [69]. The rms deflection angle for an UHECR of charge Ze is found to be

\[
\delta_{rms} \approx 3.6 Z E_{11}^{-1} kpc^{-1/2} \lambda_{kpc}^{-1/2} B_{\mu G, rms} ,
\] (8)

where \( B_{\mu G, rms} \) is the rms strength of the magnetic field in \( \mu G \), \( E_{11} \) is the UHECR energy in units of \( 10^{11} \) GeV, \( r_{kpc} \) is the distance over which the magnetic fields act in kpc, and \( \lambda_{kpc} \) is the magnetic-field coherence length also in units of kpc [71]. The scattering in the magnetic field also gives a time spread [72,73], which is given by

\[
\tau \approx 4.1 \left( \frac{r_{kpc} B_{\mu G}}{E_{11}} \right)^2 \lambda_{kpc} Z^2 \text{ yr} \\
\approx 4.1 \left( \frac{\delta_{rms}}{3.6} \right)^2 r_{kpc} \text{ yr} .
\] (9)

Because all the UHECR scattering occurs inside the Galaxy, we have \( r_{kpc} \approx 10 \) and \( \delta_{rms} \approx 20^\circ \), yielding a dispersion of \( \tau \approx 10^3 \text{ yr} \) in the UHECR arrival times. For a source at a distance \( D \), the required isotropic equivalent luminosity is \( L_{iso} = 4\pi D^2 F_{hs} \) and so the isotropic-equivalent energy implied is \( E_{iso} > 10^{51} \xi_{1.7} \text{ erg} \). It is noteworthy that llGRBs struggle to meet this constraint as they all have \( E_{iso} < 10^{50} \text{ erg} \) [19,20]. This is also the case for SNe with relativistic outflows but without GRB counterparts, for which the observed isotropic-equivalent energy is on the order of \( 10^{49} \text{ erg} \).

- We now comment on the possibility that the main hypothesis of our analysis is false; namely, that the host metallicity is not a good indicator of the llGRB production rate (see e.g. [74–76] for a discussion on other considerations that could affect the LGRB production efficiency). In this direction, it is natural to envision the most straightforward scenario, in which the llGRB rate is independent of all factors other than the overall rate of star-formation itself. This would imply that a fixed fraction of all newly-formed stars could explode as llGRBs without perception to any of the chemical, physical, or other properties of the galaxy in which those stars formed. From the observational viewpoint, this entails that llGRBs should stochastically sample the locations of cosmic star-formation throughout the volume of the Universe in which they can be observed. The probability that any given galaxy will host a llGRB during some period of time would then be proportional to its star-formation rate. Now, given the ubiquity of llGRBs in this simplistic scenario we can ask ourselves why the correlation of UHECRs with starburst galaxies would be explained by the presence of this common phenomenon. Rather there must be some other inherently unique feature(s) of starburst galaxies to account for this correlation. Starburst galaxies represent about 1\% of the fraction of galaxies containing star-forming galaxies [80], and the probability of SN explosions is about an order of magnitude larger in starbursts than in normal galaxies, e.g., the SN rate for M82 is about \( 0.2 - 0.3 \text{ yr}^{-1} \) [81] whereas for the Milky Way is \( 3.5 \pm 1.5 \text{ century}^{-1} \) [82].
Note that these two effects tend to compensate each other, and so if the anisotropy signal reported by the Auger Collaboration originates in Î­GRBs (within this particular underlying scenario), then when studying the correlation of UHECRs with the nearby matter distribution the statistical significance must increase. However, when all sources beyond 1 Mpc (i.e. effectively taking out the Local Group) from the 2MRS catalog are included as part of the anisotropic signal in the analysis of [4] the significance level reduces from 4.5σ to 3.8σ. Altogether, the data yielding the anisotropy signal seem to favor a production mechanism of UHECRs above 38 EeV which is exclusive to starbursts, like Fermi-shock acceleration in starburst superwinds.

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