Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
Proceedings IAU Symposium No. 363, 2023
E. Troja & M. G. Baring, eds.
doi:10.1017/S1743921322001107

Identification of a Local Sample of Gamma-Ray Bursts Consistent with a Magnetar Giant Flare Origin

Michela Negro[1,2,3] **and Eric Burns**[4]

[1]University of Maryland, Baltimore County, Baltimore, MD 21250, USA

[2]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

[3]CRESST, NASA/GSFC, Greenbelt, MD 20771, US
email: mnegro1@umbc.edu

[4]Louisiana State University: Baton Rouge, LA, US
email: eric.burns@lsu.edu

Abstract. Triggered by the MGF detected from the Sculptor galaxy on April 2020, the study described in this proceeding reports the unambiguous identification of a distinct population of 4 local (< 5 Mpc) short GRBs, whose rise time and isotropic energy release are independently inconsistent with the larger short GRB population at $> 99.9\%$ confidence. These properties, the host galaxies, and non-detection in gravitational waves all point to an extragalactic MGF origin. The inferred volumetric rates for events above 4×10^{44} erg of $R = 3.8^{+4.0}_{-3.1} \times 10^5 Gpc^{-3} yr^{-1}$. These rates imply that some magnetars produce multiple MGFs, providing a source of repeating GRBs. The rates and host galaxies favor common core-collapse supernova as key progenitors of magnetars.

1. Introduction

Glitches, bursts, outbursts, quasi-periodic oscillations, giant flares are examples of the varied transient activity of magnetars, highly magnetized, young neutron stars (see e.g. Kaspi & Beloborodov (2017) for a recent review). The Galactic MGF sample counts hree events: two detected in our Galaxy (Hurley et al. (1999, 2005)), and one in the Large Magellanic Cloud (LMC) Evans et al. (1980). MGFs are characterized by a total energy release of over 10^{44} erg s^{-1} in the X-ray and soft gamma-ray band. The Galactic events, after a short (ms-long) energetic prompt spike, showed a characteristic periodic tales, decaying with time (lasting up to hundreds of seconds). Given this extremely large energy release these events, when extragalactic in origin, MGFs would appear as short GRBs (Hurley et al. (2005)) and, if close enough, are detectable by active gamma-ray burst monitors. Indeed in 2005 and 2007, two extragalactic MGFs were observed (see e.g Ofek et al. (2006), Mazets et al. (2008)) and associated to M81 and M83 galaxies. Lower and upper limits on the fraction of detected short GRBs with MGF origin has been set to between 1% and 8% (see e.g. Popov et al. (2006); Ofek (2007); Svinkin et al. (2015)).

On April 15 2020, GRB 200415A was added as a new member of the detected MGF population, hence 3 extragalactic events. Such event triggered our new population study, described in the following sections. This proceeding is based on a recent publication of Burns et al. (2021), to which we refer for a detailed discussion of methods and results. For

https://doi.org/10.1017/S1743921322001107 Published online by Cambridge University Press

more information about the event that triggered this study, GRB 200415A (Svinkin et al. (2021), Roberts et al. (2021), Ajello et al. (2021)).

2. Data samples and analysis

The goal of the analysis was to estimate the probability that a given position in the sky (where a short GRB happened) is to produce a MGF with a particular fluence at Earth. We pixeled the sky using HEALPix format sky maps with NSIDE=8192 (pixel width of ≈0.5 arcmin) and the above mentioned probability is defined as

$$\Omega = 4\pi \sum_i \frac{P_i^{GRB} P_i^{MGF}}{A_i} \tag{2.1}$$

where the sum runs over the pixels, A_i is the pixel area, P_i^{GRB} is the GRB probability distribution function at the i^{th} sky position (given by the localization uncertainty of the GRB). P_i^{MGF} is the probability that a given position is to produce a MGF with a particular fluence at Earth, defined as

$$P_i^{MGF} = \mathrm{SFR}_i \mathrm{PDF}(E_{iso}) \tag{2.2}$$

where PDF(E_{iso}) is the probability distribution function of the MGF intrinsic energetic (E_{iso}) modeled as a power law whose index we estimated to be $\alpha = 1.3 \pm 0.9$ at 90% confidence iterating over the E_{iso} values of the previously known MGFs (excluding the first event in the LMG, given the different IPN calibration).

The GRB sample has been obtained combining several GRB monitors observations (CGRO-BATSE, Konus-WIND, Swift-BAT and Fermi-GBM), and exploiting information from the IPN data. Our final selection consisted into 250 short GRB (according to the standard definition of T90 $<$ 2 s), with measured bolometric (1 keV − 10 MeV) fluences at Earth and a good localization (90% confidence area $<$4.125 deg^2).

To build the local sample of galaxies, we used the z=0 Multiwavelength Galaxy Synthesis (z0MGS) Catalog, which combines GALEX ultraviolet observations and WISE infrared observations. We also supplemented the missing information with the the Census of the Local Universe (CLU), which additionally provides the angular size of the galaxies (extended sources are modeled as ellipses). We selected $>$100,000 galaxies between 0.5 Mpc (excluding the Milky Way and its satellite galaxies) and 200 Mpc (way beyond where MGFs can be detected).

Figure 1 (left panel) shows the inverse cumulative Ω function: the blue shaded regions correspond to the null hypothesis (GRB have a non-local origin) and is obtained randomly rotating the galaxy sample in the sky and repeating the Ω computation; the orange line correspond to the real short GRB sample. Four events deviate form the background at more than 5 sigma, unambiguously identifying a new class of GRBs. Our search identified the recent event GRB 200415A (from the Sculptor galaxy), GRB 051103 and GRB 070201 (associated to M81 and M31 respectively), which are two of the previously known extragalactic MGFs, and additionally, it found a new event, GRB 070222, associated to M83. This brings the population of detected MGFs up to 7 events.

We used the entire population (excluding the first 1979 event, because of the different IPN sensitivity), to constrain the intrinsic energetic power law index. To do that we simulated a large number of extragalactic MGFs assigned to a specific host galaxy following a power-law intrinsic energetic distribution with index α. The MGFs that could be detected are those whose sampled E_{iso} and distance produce a flux greater than our detection threshold. We used a Anderson-Darling k-sample test to compare the detected simulated populations to the real one (4 extragalactic MGFs). We scan a wide range of α and find that $\alpha = 1.7 \pm 0.4$ is the best range to reproduce our observations.

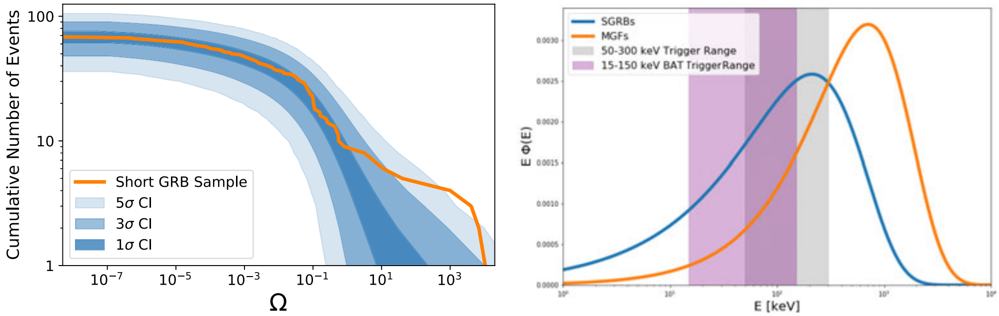

Figure 1. Left: Ω is a statistic that ranks how believable the event is to be an extragalactic MGF, with values for the true population is shown in orange. The background confidence intervals at 1, 3, and 5σ are shown in blue. The four most significant events together surpass 5σ discovery significance. Right: Comptonized spectra for a typical short GRB of cosmological origin (blue) and for GRB 200415A (orange) of MGF origin. The shaded regions mark the typical trigger range for *Fermi*-GBM (gray) and *Swift*-BAT purple).

The intrinsic energetic PDF and the number of detected events gives an estimation of the intrinsic rate of MGFs in the local universe: we find an intrinsic volumetric rate for events above 4×10^{44} erg of $R = 3.8^{+4.0}_{-3.1} \times 10^5 Gpc^{-3} yr^{-1}$, which places MGFs as the dominant gamma-ray transient that have been detected from extragalactic sources.

A competitive rate from a class of transient events is, e.g., the intrinsic rate of local core-collapse supernovae (CCSN) (see, e.g., Li et al.,).

3. Results and Discussion

We found a sample of 4 short GRBs that are incompatible with a non-local origin at more than 99.9% (>5 sigma) confidence. The four events differ from cosmological short GRBs by having significantly shorter rising time and several order of magnitude lower E_{iso}. Figure 2 shows the 4 MGFs (orange) compared to the cosmological short GRB population (blue). The values of rise time and intrinsic energetic for the galactic MGFs are also marked (gray dashed lines). the identified short GRBs are extremely short (a few milli-seconds) and show an intrinsic energetic 5 order of magnitude lower than typical SGRB powered by neutron star mergers.

The estimated volumetric rate and the type of host galaxies (with high star formation rates), favor CCSN as the dominant formation channel for magnetars, with at least 0.5% of CCSN resulting in magnetars. At the same time, the result suggests that some magnetars produce multiple MGFs: this would be the first known source of repeating GRBs.

The inferred volumetric rate places MGFs as the dominant gamma-ray transients that can be detected at extragalactic distances. On the other hand we only detected 7 in the past four decades. The explanation to this can be found in the atypical spectrum of these short GRBs: with respect to GRB with cosmological origin, the prompt emission of there events (modelled as a Comptonized spectrum) show a higher peak energy (1.5 MeV compared to 0.6 for typical short GRBs) and a greater spectral index (∼0 compared to ∼0.4 for typical short GRBs) Roberts et al. (2021). This is enough to move the peak of the emission away from the trigger range of current GRB monitors, as shown in Figure 1 (right panel).

Such a high volumetric rate has several implications relevant for future missions operating in the soft-gamma-ray regime: more sensitive instruments than the currently operating will be able to detect several more extragalactic MGFs from more distant Galaxy. The recent work by Martinez-Castellanos et al. (2021), for example, estimates

https://doi.org/10.1017/S1743921322001107 Published online by Cambridge University Press

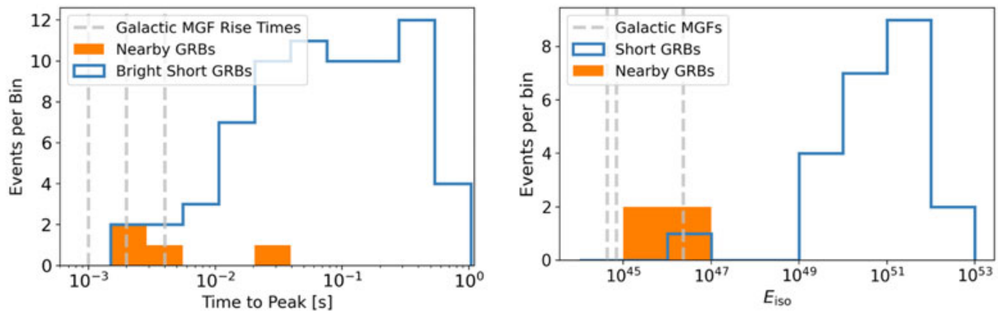

Figure 2. Left: time-to-peak for the 4 identified extragalactic MGFs (orange) compared to the cosmological short GRB population (blue). Right: E_{iso} for the 4 identified extragalactic MGFs (orange) compared to the cosmological short GRB population (blue). The gray dashed lines mark the parameters values derived for the prompt emission of the Galactic MGFs.

that the future mission concept *AMEGO-X* will recover 1 to 19 local MGFs (90% C.L.) within 25 Mpc for a 3 year mission. The future mission *Starburst* link will detect between 1 and 6 MGFs (90% C.L.) within 25 Mpc for 1 year.

We would like to acknowledge all the authors of the paper in Ref Burns et al. 2021, who contributed to this result. In particular: Dimitry Svinkin, Kavin Hurley, Zorawar Wadiasingh, Georges Younes, Rachel Hamburg, Anna Ridnaia and David Cook.

References

Ajello, M. et al. *Fermi*-LAT Collaboration. Nature Astronomy, vol 5, page 385, 2021.
Burns E. et al., ApJL, 907(2):L28, 2021
Evans, W. et al., Astrophys. J., 237, L7, 1980.
Hurley, K., Cline, T., Mazets, E., et al., Nature, 397, 41, 1999a.
Hurley, K., Boggs, S., Smith, D., et al., Nature, 434, 1098, 2005.
Kaspi V. M. et al., ARA&A, 55:261-301, 2017.
Li, W. and Chornock, R. et al., Mon. Not. R. Astron. Soc., 412, 1473–1507, 2011.
Martinez-Castellanos I., et al., 2021, (ApJ submitted), Pre-print: arXiv:2111.09209.
Mazets, E. P., Aptekar, R. L., Cline, T. L., et al., Astrophys. J., 680, 545, 2008.
Ofek, E. O., Kulkarni, S., Nakar, E., et al., Astrophys J., 652, 507, 2006.
Ofek, E. O. 2007, Astrophys. J., 659, 339
Popov, S. B., Stern, B., Mon. Not. R. Astron. Soc., 365, 885, 2006.
Roberts, O. J. et al., Nature, 589(7841):207-210, 2021.
Svinkin, D. et al., Nature, 589(7841): 211-213, 2021.
Svinkin, D. et al., Mon. Not. R. Astron. Soc., 447, 1028, 2015.
https://science.nasa.gov/astrophysics/programs/astrophysics-pioneers

https://doi.org/10.1017/S1743921322001107 Published online by Cambridge University Press