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/S1743921322000795

Radio afterglows of Very High Energy Gamma-ray Bursts

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Abstract. Five long gamma-ray bursts (GRBs) have been found to have very high energy (VHE, >100GeV) counterparts. Interestingly, more than one emission mechanism has been invoked to explain the VHE counterpart from different events. As a result of this discovery, it has become apparent that we have been missing half of the energy produced in the afterglow of GRBs. We have been studying the radio afterglows in order to investigate whether these VHE GRBs have unusual jet properties. Studying these events in the radio waveband is advantageous as the emission at lower frequencies is brighter for longer enabling detailed, long term study of the jet evolution. The jet properties and environments of these GRBs vary hugely in a similar manner to that seen in the 'regular' long GRB population with evidence of bright reverse shock emission and multiple jet components. This work is presented on behalf of a much larger collaboration.

Keywords. gamma rays: bursts, radio continuum: general, ISM: jets and outflows

1. Introduction

Long Gamma-ray bursts (lGRBs) occur when massive, rotating stars undergo core collapse and launch jets via accretion onto a central compact object. We observe lGRBs as flashes of gamma-rays and hard X-rays usually lasting upwards of 2 seconds using telescopes such as the Neil Gehrels *Swift* Observatory (hereafter *Swift*). The flashes of gamma-rays are referred to as the prompt emission, thought to be produced via internal jet processes (see Levan et al. (2016) for a recent review).

The prompt emission is succeeded by an afterglow formed via external shocks: the jet accelerates ambient electrons in the circumburst medium which cool emitting synchrotron radiation (Sari et al. 1998). Most afterglow detections are dominated by a forward shock component (the jet interacting with the circumburst medium) but as the jet decelerates, a second shock moves in the opposite direction towards the compact object: a reverse shock (Sari & Piran 1999). Each shock produces its own synchrotron signature, visible from the radio to X-ray wavebands, which evolves as the jet expands. The synchrotron spectrum is formed of three break frequencies: the self-absorption break, the break corresponding to electrons with the lowest energies and the cooling break above which electrons lose a significant proportion of their energy within the dynamical timescale of the jet. The break frequencies are connected by power laws normalised to some peak flux density.

Multi-frequency, high cadence observations of the afterglow allow us to track the evolution of the synchrotron spectrum, in particular the location of the frequency breaks and the flux density at the peak of the spectrum. By tracking these observables, we can extract physical parameters describing the jet and the circumburst medium (Granot & Sari 2002).

Since 2018, five GRBs have been accompanied by detections of photons of very high energies (VHE), above 100 GeV using Cherenkov telescopes such as MAGIC and H.E.S.S. Publications on the interpretations on the detections from GRBs 180720B, 190114C and 190829A invoke either synchrotron or synchrotron self-Compton processes as the origin of the observed emission (Abdalla et al. 2019; MAGIC Collaboration et al. 2019; H.E.S.S. Collaboration et al. 2021). Detailed observations of future VHE GRBs are required to determine which is the most likely mechanism.

2. Radio observations and results

At radio frequencies, the afterglow is more luminous for longer - years in some cases. We use radio interferometers, including the Karl Jansky Very Large Array and MeerKAT, to observe the afterglow emission of VHE GRBs. The evolution of the low frequency emission is heavily dependent on the jet physics and circumburst environment. Therefore by tracking the radio emission with time, we can infer these properties. All five VHE GRBs have strong radio detections up to 100 days post-burst. Figure 1 shows the radio afterglow light curves of GRB 190829A from Rhodes et al. (2020), one of the highest cadence radio light curves of any GRB to date. The radio data showed evidence of two separate shock components in the two different frequency light curves. The emission observed using AMI-LA at 15.5 GHz shows a decaying broken power law over laying an additional component of constant flux density, we interpret the 15.5 GHz light curve as a combination of the reverse shock and the host galaxy. The emission at 1.3 GHz MeerKAT light curve also forms a broken power law and is most likely from the forward shock. MeerKAT has at least four times higher angular resolution compared to AMI-LA meaning that we were able to spatially resolve the host galaxy and afterglow.

Forward shock emission has been inferred from the radio observations of all five VHE GRBs. The outstanding temporal and frequency coverage of each event allows us to test the underlying assumptions of afterglow models and search for new emission components. For example in GRB 190114C, the detection of linearly polarised emission from the reverse shock allowed (Laskar et al. 2019) to constrain the magnetic field structure in the jet. To fit afterglow models to the observed data, more complex assumptions are required, time varying jet microphysics was required (Misra et al. 2021). For GRB 201216C, detections made over 30 days after the burst at 1.3 GHz imply the presence of a wider, low energy, outflow component (a cocoon) in addition to the highly collimated ultra-relativistic jet (Rhodes et al. 2022). Cocoons are thought to be produced as the jet propagates through the infalling stellar material, dumping energy into said material and causing a slower expanding component.

3. Are VHE GRBs different?

The detections of VHE GRBs are very rare with a detection rate of one every nine months (*Swift* detects about 100 lGRBs every year). With only five VHE GRBs, we are limited in how confident we can be of the results of any comparison between VHE GRBs and the rest of the lGRB population. In Rhodes et al. (2020), we showed that both VHE GRBs and those without VHE detections or observations were consistent with originating

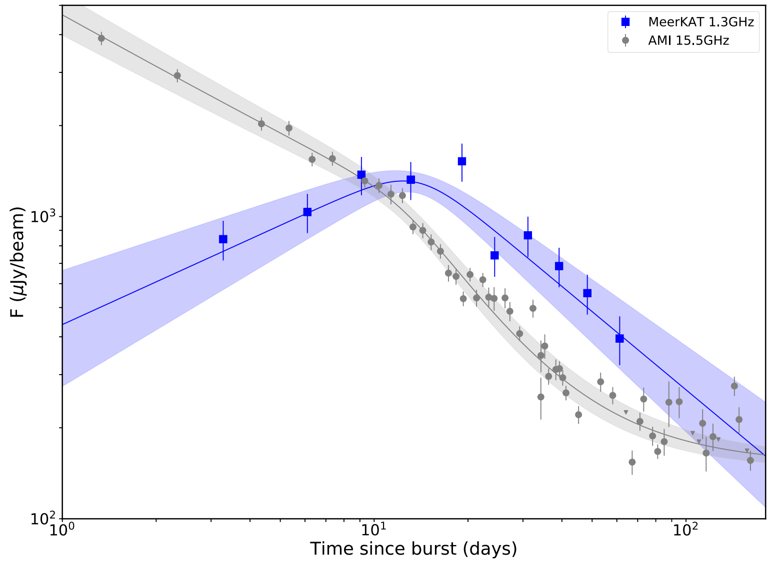

Figure 1. Radio afterglow light curves at 1.3 and 15.5 GHz for VHE GRB 190829A (Rhodes et al. 2020).

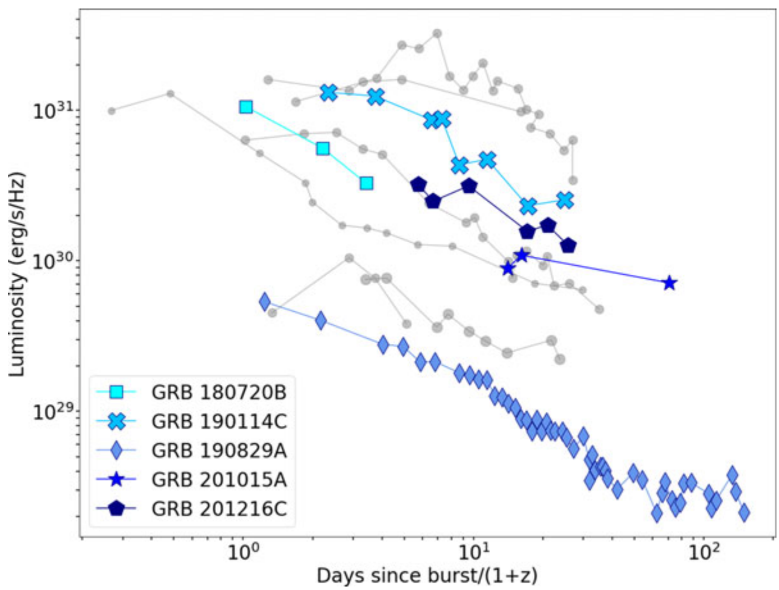

Figure 2. Radio luminosity light curves spanning 1.3–15.5 GHz for all five VHE GRBs to date overlaid on a sensitivity limited sample of low-redshift, 'regular' lGRBs (Rhodes et al. 2020). The data from GRB 201015A and 201216C come from Giarratana et al. (2022) and Rhodes et al. (2022).

from the same radio luminosity distribution. Figure 2 shows radio luminosities of the VHE GRBs to date overlaid on a sensitivity limited sample of low redshift lGRBs.

As the sample size grows, with such excellent coverage, we can search for similarities and differences between the two samples not only in terms of luminosity but also in the microphysics and the jet environment. Very preliminary analysis hints at a possible disparity between the distributions of the fraction of energy given to the magnetic fields

https://doi.org/10.1017/S1743921322000795 Published online by Cambridge University Press

in the two populations. A two-sample KS tests shows that currently the disparity is not statistically significant.

At the current detection rate it will take time to create a large sample of VHE GRB afterglows in order to determine any dichotomies at a statistically significant level. However this does afford the opportunity to have dedicated collaborative multi-wavelength follow up campaigns for each event. As the population grows, we shall be able to analyse the VHE GRB population as a whole to search for any trends within the population and differences compared to those events without VHE detections.

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