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Observing transients with LOFAR and AARTFAAC

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The Low Frequency Array (LOFAR) is a new European radio telescope operating at 30-240 MHz. LOFAR will offer an exciting opportunity to study the radio emission from GRBs at timescales from first detection until years afterwards. I will describe the features LOFAR will be able to use to study GRBs including:

- Dedicated and commensal real-time monitoring programmes enabling detection and monitoring of radio afterglows.
- Fast, automated response to targets of opportunity.
- A raw data buffer, providing the ability to "re-observe" past events at high time, spectral and spatial resolution.
- Rapidly sharing newly detected transients using VOEvents.

Additionally, the AARTFAAC Project will build upon the core LOFAR capabilities to provide an all-sky real-time monitor for bright transients.

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Figure 1: This figure shows the 6 most central stations of LOFAR. In the top left corner is an example LBA and the bottom right corner shows an example HBA. (Images credit [11, 2])

1. Introduction

The Low Frequency Array (LOFAR) is a radio telescope which has a core collecting area in The Netherlands but also has international stations in France, Germany, Sweden and the UK [11]. It operates in two bands: the Low Band Antenna (LBA) with a frequency range of 30–80 MHz and the High Band Antenna (HBA) with a frequency range of 120–240 MHz. The frequency gap corresponds to the FM radio bands. Figure 1 shows the 6 most central stations of LOFAR and examples of the LBA and HBA antennae.

One of the LOFAR key science projects is the Transients Key Science Project which detects and monitors transient and variable sources, such as gamma-ray bursts (GRBs), X-ray binaries and pulsars, using both time-series and image-plane data [12, 6]. LOFAR will be able to explore exciting new regions of parameter space for GRBs. This paper will describe a selection of features which LOFAR will be able to use to study GRBs from the initial trigger untill years afterwards.

2. Monitoring Transient Sources

Much of the imaged data produced by LOFAR will be searched for transient sources using the transients pipeline [23] and this will ultimately be in near real-time (still to be implemented) enabling LOFAR to trigger other instruments via VOEvents [4]. The transients pipeline will provide catalogued source associations and lightcurves. Sources can also be included in a user defined monitoring list so that a flux is measured at the position of the source each time the field is observed.

The long-term monitoring of sources will provide lightcurves which will be ideal for the study of radio afterglows of GRBs. It is becoming increasingly clear in simulations that the jets of GRBs do not start to spread laterally and become roughly spherical until very late times, years after the

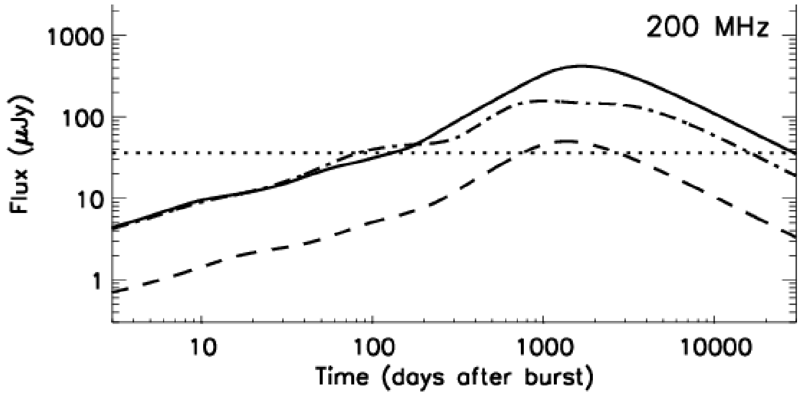

Figure 2: This is the predicted radio afterglow for GRB 0303029 at 200 MHz (from [27]). It was extrapolated to 200 MHz from radio observations at higher frequencies. The dotted line represents the predicted sensitivity of LOFAR in a 4 hour observation. The solid and dash-dot lines represent 2 different models for the radio emission. The dashed line represents the solid line redshifted to z=1 [27].

trigger, when the afterglow spectrum is peaking in the LOFAR frequency range [25, 26, 3]. This is very important as the source needs to be approximately spherical in order to obtain the true energy of the GRB. These observations can also be used to constrain jet parameters, surrounding medium properties, observing angles and microphysics. An example lightcurve for GRB 030329 is shown in 2 and shows that the afterglow would be detectable for months to decades after the trigger [27].

An alternative source of radio emission has been predicted for short GRBs (with $T_{90} \leq 2$ s [9]). The progenitor system of short GRBs is thought to be the merger of two neutron stars or a neutron star and a black hole. These compact binary mergers are predicted to have sub-relativistic outflows which may produce a radio flare, detectable by LOFAR on the timescale of weeks to years after the initial trigger [14, 18, 16]. Detection of this emission would enable the determinaton of the density of the surrounding medium and more properties of the progenitor system.

As LOFAR will be monitoring the radio sky via the transient pipeline, it also will be able to discover orphan radio afterglows of GRBs. These may be orphan afterglows due to being beamed away from us and we observe the radio emission due to the late-time spreading of the jet, which will be identifiable by using predicted off-axis radio lightcurves [25, 26]. Alternatively, some orphan afterglows will be simply due to missing the prompt GRB emission (e.g. if there was not a sufficiently sensitive gamma-ray detector pointing in this direction at the time of the GRB). The detection of orphan afterglows will enable the determination of the GRB rates and constraints on the beaming angle of the jet (e.g. [8]).

3. Automated Response

In the future, it will be possible to trigger LOFAR using VOEvents. As a fully electronic telescope, which does not require time to slew, observations will be able to start soon after receiving a VOEvent trigger. This method has been recently tested using the Arcminute MicroKelvin Imager (AMI, 13.5–18 GHz [22]), which is typically slewing to GRBs within 4–5 minutes after the GRB trigger time, although this is not the full implementation of the LOFAR system.

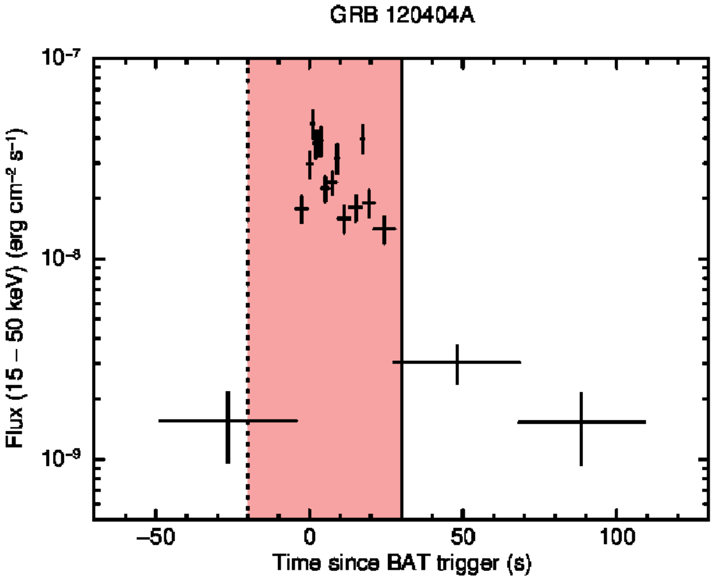

Figure 3: This figure illustrates the duration that the transient buffer boards could store at 10% bandwidth, assuming a trigger is recieved 30 s after the trigger time from an instrument such as *Swift*. The durations are superimposed on the BAT 15–50 keV light curve of GRB 120404A (obtained from the *Swift* burst analyser website [5]), which had a typical duration of $\sim$35 s. The solid line marks the time at which the transient buffer boards could be triggered by a VOEvent from *Swift* and the shaded region, covering much of the time of the prompt GRB emission, could be searched for radio emission.

Any coherent radio pulse which may be associated with the prompt GRB emission (e.g. [24, 19, 7]) will be dispersed due to plasma between the source and the observer. This makes the prompt emission arrive much later at very low frequencies. Therefore rapid follow-up observations by LOFAR would be able to probe this regime and place constraints on any low frequency radio emission associated with the prompt emission.

The most promising prediction for early radio emission is from reverse shocks [10], which are expected to occur within the first hours after the GRB [13]. This is a time regime which both AMI and LOFAR will be able to systematically probe at different frequencies due to their rapid response times to triggers. These early-time radio observations will be able to place constraints on the physical parameters of the shock and provide clues about the nature of the jet (e.g. whether the jet is Poynting flux dominated or a baryonic outflow [15]).

4. Transient Buffer Boards

The transient buffer boards, a feature unique to LOFAR, are RAM buffers on each station which store 1.3 s of raw data [20]. They are being upgraded to enable $\sim$5 s of data to be stored and future software upgrades will enable the trade off of bandwidth for time, e.g. at 10% bandwidth they would be able to store $\sim$50 s. Assuming 10% bandwidth, the data that the transient buffer boards would be able to store relative to a typical duration GRB is shown in Figure 3.

The transient buffer boards will be frozen via an internal trigger from LOFAR or external trigger (e.g. VOEvents), to be correlated and imaged at a later time. The data can be used to form an image in any direction for the LBA or within 10000 square degrees for the HBA (which data are stored, HBA or LBA, will depend on the observations being conducted at the time). This image can then be searched for a radio source associated with the GRB. Full time series data will also be stored which will enable the search for coherent pulses during the prompt emission of GRBs (using a similar method to that used for the search of pulsar bursts, as described in e.g. [21]). The radio signal dispersion means the data stored may provide information from several minutes before the GRB, enabling the search for radio precursors. Therefore, the transient buffer boards enable the exploration of a new discovery space for GRBs.

5. AARTFAAC

Amsterdam-ASTRON Radio Transient Facility And Analysis Centre (AARTFAAC [17, 1]) will use the 6 most central LOFAR stations with a dedicated hardware correlator and separate imaging software pipeline which will produce images every second. These images will be analysed by the transient pipeline giving triggers in near real-time. It will be opperational at all times in a commensal mode using either the HBA or the LBA (depending on the observations that LOFAR is undertaking at the time) giving shallow, low resolution images of 1000 square degrees or whole sky respectively.

AARTFAAC will probe a yet unstudied parameter space as this is one of the first all-sky monitors at radio wavelengths, enabling the discovery of the brightest and rarest radio transients.

6. Conclusions

LOFAR will be able to monitor GRB radio afterglows over long timescales providing an invaluable resource for the study of GRB energetics and microphysics parameters. Via the detection and monitoring of candidate orphan afterglows, LOFAR will also be able to place constraints on the maximum beaming angles and GRB rates.

Additionally, LOFAR will explore a whole new parameter space for GRBs, as it will be able to study GRB early-time radio emission via the rapid triggering, transient buffer boards and the AARTFAAC project. This will provide opportunities to make new discoveries for example radio precursors, coherent prompt emission, reverse shocks and the unknown.

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