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Finding fast radio bursts

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Abstract. A new class of dispersed radio bursts have been reported with the Parkes 64 m radio telescope by Thornton et al. (2013) as part of a large-scale survey for pulsars and fast transients. If the dispersion measures of the bursts are interpreted in the context of the standard galactic and cosmological models the bursts would originate from cosmological distances making them a powerful probe of the ionised intergalactic medium. In this paper we briefly review the evidence for the bursts, their potential link to the "Perytons" reported by Burke-Spolaor et al. (2011) and on efforts to refurbish the Molonglo Observatory Synthesis Telescope to find bursts more frequently.

Keywords : fast radio bursts

1. Introduction

Over the last two decades brilliant bursts of light from very distant, exploding stars have transformed our understanding of the Cosmos. In gamma-rays, bursts have elucidated the fate of the most massive stars and enabled new probes of the evolution of the Cosmos and the physics of black hole formation (Kulkarni et al. 1998). At optical wavelengths, Type Ia supernovae have provided standard candles with which to measure the acceleration of the Universe and show the existence of "dark energy", resulting in the awarding of the 2011 Nobel prize (Riess et al. 1998, Perlmutter et al. 1999). At radio wavelengths a new type of burst was reported by (Lorimer et al. 2007) and caused a great deal of excitement. The few millisecond-long pulse exhibited the dispersion sweep often observed in pulsars, but the magnitude of the dispersion seemed to imply that the source was at cosmological distances. Was it a unique new probe of the Universe?

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The burst was found in Parkes radio telescope archival data, and was so bright that it saturated the 1-bit digitizers in the analogue filterbank system built for the Parkes multibeam pulsar surveys (Manchester et al. 2001). The standard model of cosmology posits that most of the ordinary matter (i.e. baryons) along intergalactic lines of sight is in the form of ionized gas – but which is notoriously difficult to probe directly. The Lorimer burst could represent the long sought class of object able to probe the evolution of the baryonic content of the Universe over a significant fraction of its lifetime.

Years later, Keane et al. (2011) reported the discovery of what could have been a second Lorimer burst, but with some ambiguity because of its proximity to the Galactic plane (suggesting it may be a Galactic rather than an extragalactic source), while numerous other studies had turned up no bursts at all (eg Burke-Spolaor & Bailes 2010, Siemion et al. 2012, Bagchi, Nieves & McLaughlin (2012). Disturbingly Burke-Spolaor et al. (2011) discovered a source of transient events that suggested the Lorimer event was potentially connected to terrestrial lightning or possibly other radio interference (Kocz et al. 2012). Burke-Spolaor et al. dubbed these events "Perytons", because they were of unknown origin.

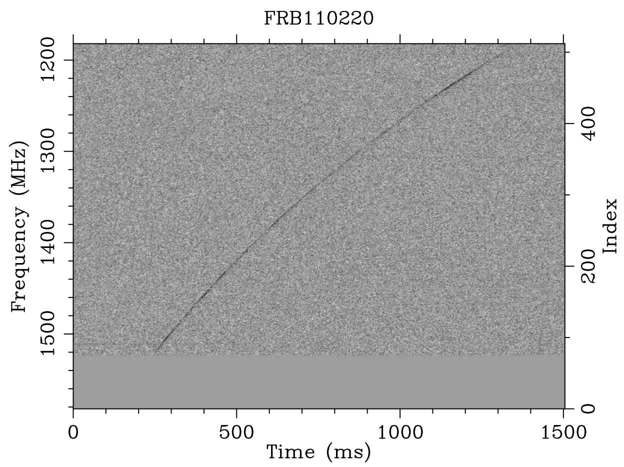

Figure 1. Waterfall plot of FRB110220 showing pulse intensity as a function of radio frequency and time. The pulse exhibits the classic f^{-2} dispersion sweep to high accuracy and becomes broader at low frequencies consistent with interstellar scattering relations. The band is blanked above ~1510 MHz due to an interfering satellite phone service and some channels are deleted because of other sources of narrow band radio frequency interference. See Thornton et al. (2013) for more details.

This confusing situation changed when a survey for pulsars of regions away from the Milky Way plane yielded four new fast radio bursts (Thornton et al. 2013). The brightest of these bursts (Fig 1.) has a very large dispersion (945±1 pc cm^{-3}) and used a new digital "backend" at the Parkes 64 m radio telescope based upon the CASPER

ROACH boards. This meant that its dispersion and temporal properties could be determined with much higher accuracy than for the Lorimer event. Thornton et al. (2013) dubbed these phenomena Fast Radio Bursts (FRBs). Real, "celestial" pulses should exhibit a temporal delay with respect to frequency of f^{-2}, and a scattering width proportional to frequency f^{-4}. The frequency delay of the brightest burst was measured to high accuracy, yielding a power law index of –2.000(6), and its scattering relation index was –4.0(4), making a celestial origin case quite persuasive. The burst also appeared in just one of the 13 beams of the receiver, making its celestial origin yet more probable. The three other bursts possessed dispersions of 553, 723 and 1104 pc cm^{-3}, and signal-to-noise ratios that helped populate a characteristic log-N, log-S distribution more typical of a cosmological population than the isolated and extremely high signal-to-noise Lorimer event.

Since the Thornton et al. paper another FRB was detected in archival data in the Jacoby et al. (2009) survey by Burke-Spolaor & Bannister (2014), and more importantly, a highly-dispersed pulse, far in excess of the dispersion expected from galactic models was detected as part of the PALFA survey in the galactic anti-centre region (Laura Spitler, private communication). Many telescopes are now searching for FRBs at other wavelengths (eg Tingay this volume, Trott, Tingay & Wayth 2013) and pulsar data is being reviewed from other archival and ongoing surveys with much greater dispersion measure ranges. Depending upon extra-galactic scattering relations and the intrinsic spectral index of the FRBs, we would expect any survey that can detect a large number of pulsars at high dispersion measures to also detect FRBs. FRB detection rates for various planned surveys and telescopes can be found in Hassall, Keane & Fender (2013) although we might expect the Green Bank Telescope's drift scan surveys (e.g. Boyles et al. 2013), the PALFA surveys (Cordes et al. 2006) or the Northern High Time Resolution Universe surveys (Barr et al. 2013) to be excellent FRB detectors.

Until the link (if any) between FRBs and Perytons is established, or the FRBs are routinely detected at other observatories their celestial origin will remain controversial. In a recent paper, Kulkarni et al. (2014) carefully looked at models for the FRBs, their potential relation to the "Perytons" and they concluded that a single detection with an interferometer would settle the celestial vs local origin for the FRBs. A clever method of using very long baseline interferometry data for FRB discovery is described in Wayth et al. (2012) in the VFAST-R project, but the anticipated event rate is low, and this survey is yet to discover any events. In this paper we discuss potential FRB event rates and then describe a supercomputer that will use data from the Molonglo Observatory Synthesis Telescope to search for FRBs in the future.

2. FRB discovery rates

If FRBs are an isotropic cosmological population we would expect them to be detectable at any observatory with sufficient sensitivity and on-sky time. However the vast majority of FRBs have been discovered at the Parkes radio observatory, and only when looking far from the galactic plane, and so it is reasonable to ask whether this is expected or not? As it turns out the majority of 20cm pulsar surveys have concentrated on the galactic plane, where dispersive effects are significant, and bursts may be scattered by the interstellar medium. Petroff et al. (2014) recently reprocessed the High Time Resolution Universe (HTRU) "medlat" survey (Keith et al. 2010) for FRBs and found none. This result was somewhat unexpected. Firstly, if FRBs were some form of obscure interference they should appear at the same rate no matter where we look in the Galaxy, as their emission would be superimposed on otherwise noise-like data. The HTRU medlat survey spent roughly twice as much time on sky as the Thornton et al. (2013) survey had to discover four events, and so if the FRBs were some form of regularly occurring interference Petroff et al. (2014) estimate that it should have found ~9 of them. On the other hand, if FRBs really are a cosmological population then the discovery rate near the galactic plane is harder to determine as it requires synthesising surveys and attempting to compensate for the effects of the Milky Way galaxy on dispersion measure, scattering and sky brightness temperature. The HTRU medlat survey only extended to $||b|| < 15^o$ and simple models of scattering and sky brightness temperature suggest that although some bursts would be rendered undetectable by the galaxy, many would still get through. The Petroff results are therefore inconclusive.

The FRB event rate at Parkes is also frustratingly low. New FRBs have been found in the high latitude HTRU survey since the Thornton et al. results, but the telescope's duty cycle for off-plane pulsar surveys means that only 3-4 events per year are occurring, so progress in is slow.

3. A new dedicated FRB search instrument

The Molonglo Observatory Synthesis Telescope is a parabolic cylindrical telescope with 18,000 m^2 of collecting area situated in rural New South Wales just east of Canberra and operated by the University of Sydney (Mills 1981). It is comprised of 88 bays, each of which consists of 88 ring antennae that are sensitive to circularly polarised light. The bays use an ingenuous system that rotates the ring antennae to point the telescope east-west using a phased array concept. To point north-south the whole antenna tilts and it can observe between declinations of $-90^o < \delta < +18^o$. The telescope has been operating at 843 MHz for a few decades, but with a bandwidth of only 3 MHz. In its old configuration the telescope produced 88 fan beams on the sky across an elliptical area of approximately 2×1.3 square degrees. In the mid-2000s a project (SKAMP) was commenced to upgrade the telescope to a more flexible digital system that further sub-divided the 88 bays into four “modules" to give it a wider field of view and would used a digital FPGA correlator (Adams, Bunton & Kesteven 2004).

In 2013 Swinburne University of Technology joined the project and agreed to provide a supercomputer that could operate as a very flexible correlator for the telescope.

The CSIRO's CASS division produced a polyphase filterbank (PFB) to accept 100 MHz of bandwidth from each of the 352 modules. In the original design, each module would send 100 MHz of a single circular polarisation back to the PFB, the band would then be subdivided into 128 coarse filterbank channels, then sent via a custom mesh to an FX correlator and finally a fine grain filterbank before being passed to a computer for subsequent map making. In the new design the correlator is a cluster of commodity off the shelf servers each of which house two Nvidia graphics processing units and are connected by FDR10 infiniband, a high speed low-latency interconnect. The PFB has been modified with help from the Haystack observatory and now sends the coarse grain channels to the cluster via 10 Gb ethernet.

A persistent telecommunications carrier and the single 10 Gb port available on the PFB boards currently limits the telescope's bandwidth to 30 MHz. The system temperature is estimated to be about 70K, and the telescope's large field of view (approximately 2.1×4.2 square degrees) means it can be used to survey a large area for FRBs. The gain of the telescope is approximately 3.5 K Jy^{-1}. For surveys far from the galactic plane the FRB detection rate should be proportional to the telescope's field of view. Molonglo's small bay size (4.7 m ×11.7 m) and lower central frequency (~843 MHz) means that its primary field of view is over ten times that of the Parkes multibeam receiver that has been finding the FRBs.

If we live in a homogeneous and isotropic Universe, then volume arguments mean that a telescope with four times the limiting sensitivity $S_{\rm min}$ will be able to see twice as far and hence probe eight times the volume of a population leading to the characteristic relation that the event rate should be proportional to $S_{\rm min}^{-3/2}$. Although Parkes is some 3 times more sensitive that Molonglo, the field of view should mean that Molonglo detects bursts approximately twice as often as Parkes per on-sky time. Over recent years at Parkes only about 5% of the telescope's time has been spent surveying the off-plane region so if we can search for bursts at Molonglo 100% of the time we might expect discovery rates some 2/0.05 = 40× as often, or 50-100 events per year. We note in passing that a "transient event detector" was built in the 1980s by Amy, Large & Vaughan (1989) and reported many detections of events that they concluded must be over 1000 km distant. Their system only used a single frequency channel and prohibited them from making any firm conclusions about the sources, but it is possible that they were detecting FRBs.

4. A flexible software correlator

To discover bursts we intend to commission the instrument by firstly operating it as 352 independent telescopes using the Vela pulsar as a calibrator and folding the data using the dspsr pulsar software (van Straten & Bailes 2011). So far 52 of the 352 modules detect the Vela pulsar routinely. The infiniband network is being used as the "corner turner" to take the frequency channels and collate those with the same frequency on a channel by channel basis. A rudimentary software correlator has produced fringes on baselines of up to 1 km. The next stage will be to use an FIR filter to introduce delays and then perform a 2D fast fourier transform to create 352 fan beams on the sky as a function of frequency. The fan beam frequency channels will then be dedispersed with the Heimdall GPU dedisperser (Barsdell et al. 2012) and searched for FRBs. Any FRB detected will have its voltage data dumped to disk from a 60s ring buffer and then localized accurately in the E-W direction (roughly $43''$/SNR), where SNR is the signal-to-noise ratio of the FRB with an approximate 2 degree error in the N-S direction.

In parallel we hope to either be timing pulsars or making maps by purchasing additional GPUs. The wide field of view means that it should be possible to time up to 500 pulsars per day, often many at once, or conduct continuum or spectral line surveys over a large area of sky at the same time as searching for FRBs "in the background". Any FRB discovered can have the voltage data used to attempt to measure its "parallax", as any source within a few 1000 km will have a curved wavefront. Thus just a single FRB discovered by Molonglo will be able to rule in or out any atmospheric origin and potentially make the case for FRBs being an extragalactic population more compelling. The Molonglo telescope may ultimately be able to detect many dozens of FRBs per year if the individual modules can have their sensitivity optimised.

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