Fast Radio Bursts (FRBs) are millisecond-duration transient signals discovered over the past decade. Here we describe the scientific usefulness of FRBs, consider ongoing work at the Parkes telescope, and examine some search sensitivity and completeness considerations relevant. We also look ahead to the results from ongoing and future planned studies in the field.

**Keywords**: Fast Radio Bursts; Radio Astronomy; Radio Transients; Cosmology.

1. Scientific Motivation

Fast radio bursts (FRBs) have a story which has been told and retold many times over the past few years. This will be summarized by others in these proceedings. Here it is sufficient to say that FRBs are rare millisecond-duration radio bursts detected by high time resolution sky surveys in the radio, and that they have sparked excitement and controversy since they were first discovered in 2007. As is the case with many scientific endeavors there are perhaps two questions that matter the most: (i) what are they? and (ii) what are they good for?

There are those that have argued that FRBs are not astrophysical in nature, and there have been suggestions that they are some form of devilish radio frequency interference, although this line of inference seems to have ceased with the successful identification of the so-called ‘peryon’ RFI signals. There are those who have argued for and against a Galactic interpretation. There are those that have argued in favor of an extragalactic interpretation. Some have, over time, argued for all of the above. In getting to the bottom of what the FRB progenitors are we should draw a comparison with the quest to understand γ-ray bursts: then, as now, the solution was to localize the sky coordinates of the signals to much higher precision than had been previously done. Only then can a meaningful comparison be made with the predictions of the by-now very long list of proposed FRB models.

As well as the challenge of identifying the progenitor, or progenitors, for a new class of object, the main reason FRBs are a hot topic is due to their potential utility as cosmic probes. If a large number (hundreds to thousands) of FRBs can be detected, and be localised such that their redshifts can be measured, then this information can be used to (amongst other things) find out if the “missing baryons” are residing in the intergalactic medium, probe intergalactic magnetic fields and measure the dark energy equation of state parameter. These uses are independent of whether or not FRBs are standard (or standardisable) candles; if they are then...
there are further obvious applications.\textsuperscript{46,53}

2. Ongoing FRB searches and prospects

The Southern hemisphere component of the High Time Resolution Universe (HTRU) survey at Parkes\textsuperscript{28} ran from 2008 to January 2014. It was very successful in its main objective of finding high-dispersion measure millisecond pulsars at low Galactic latitudes,\textsuperscript{7,8,10} also making several noteworthy serendipitous discoveries such as identifying a magnetar in the radio\textsuperscript{23} and the so-called “diamond planet”\textsuperscript{2}. Additionally, HTRU South made significant strides in searches for “Lorimer bursts”\textsuperscript{36} as FRBs were then known, identifying at first four new examples\textsuperscript{58} which markedly increased interest in the field. The Northern hemisphere component of the HTRU survey began 2 years after its Southern counterpart and is still ongoing. It too has discovered pulsars\textsuperscript{5} and continues to do so, but as yet has not identified any FRBs. HTRU North has less time on sky by a factor of $\sim 3$, and a narrower field-of-view by a factor of $\sim 4.5$; however, the gain is about twice that of the Southern survey. This implies – in the simplest estimate where we assume that the number of sources $N$ scales with the flux density $S$ as $N \propto S^{-3/2}$ – that the FRB expectation of HTRU North is $\sim 2$, in comparison to HTRU South’s final yield of 9 FRBs\textsuperscript{14}.

Fueled by the results at Parkes, FRB search programs have sprung up at other telescopes and in other observing bands; these have ranged from dedicated projects to simply searching extant archival data. The first FRB not discovered at Parkes, resulted from the re-analysis of observations at 1.4 GHz taken at Arecibo.\textsuperscript{56} A fast imaging campaign searching for FRBs with 5-millisecond time resolution at 1.4 GHz has also been performed at VLA\textsuperscript{32}, with no new detection, likely due to as yet insufficient time spent on sky. Additional experiments have then been planned, e.g. the new Apertif system\textsuperscript{33} — based on phased array feed (PAF) receivers, now at the commissioning stage at WRST — offers a wealth of potential FRB discoveries in the Northern sky at 1.4 GHz.

The FRB\textsuperscript{11} detected at the Green Bank radio telescope is particularly interesting since it is the first outside of the $\sim 1.4$-GHz band, showing that FRBs can be detected at $\sim 800$ MHz. This region of the radio spectrum, is where the Molonglo Synthesis Telescope will survey the sky for FRBs. Molonglo is currently being refurbished for high time resolution studies of the sky\textsuperscript{11}, and when complete will perform continuous FRB searches with an unrivaled product of time-on-sky and field-of-view. If Molonglo’s sensitivity is sufficient (which depends on FRB spectra and the final system performance) then it could have an FRB discovery rate twice that of Parkes\textsuperscript{11}. CHIME\textsuperscript{4}, a telescope under construction in Canada, will have similar specifications to Molonglo and operate at the intermediate frequency range 400 – 800 MHz. Finally, searches at much lower frequencies are ongoing at LOFAR\textsuperscript{15} and MWA\textsuperscript{57}. However, as the shape of the FRB spectra is still unclear, the prospects for detection at frequencies below $\sim 800$ MHz remain uncertain as yet.
All in all, and except for Parkes, the various other endeavors are either yet to be completed, or are suffering from different combinations of insufficient time-on-sky, field-of-view and sensitivity. Thus, as of early 2016, Parkes remains the premiere FRB discovery instrument on the planet. At present the SUrvey for Pulsars and Extragalactic Radio Bursts (SUPERB) is underway at Parkes. This project arose at the end of 2013, when it was clear that many improvements – with respect to the aforementioned HTRU survey – could have been applied to enable a more optimized FRB survey. By that stage GPU hardware had progressed and, crucially, software to fully exploit it had been developed\(^b\). It was thus feasible to perform FRB (and pulsar) searches over a wide range of dispersion measure (and orbital accelerations).

In particular, SUPERB was devised with the following goals in mind:

- Find more FRBs.
- Find out more information per FRB than ever before.
- Perform real time pulsar and transient searches.

Experience from past experiments had shown that a major obstacle for constraining the nature of the FRBs was the long lag between the occurrence of the radio burst and the starting of any campaign aimed to identify an FRB counterpart in other electro-magnetic bands.

SUPERB was then designed in order to maximally reduce the dead time between an event and its notification to the observers in the community of the follow-up teams. In particular, a large-scale multi-wavelength collaborative effort has been constructed in parallel with the set-up of the survey. The advantages of a prompt reaction and a rapid follow-up of the most interesting events became immediately evident, when the first ‘peryton’ signal occurred during a SUPERB observation.

In fact, a quick and secure identification of the origin of these RFI signals was finally possible. Similarly, there may be cause for optimism that at least some FRBs identified with SUPERB may be localized on the sky, and thus some of the numerous scientific applications of FRBs may already be realizable. The earliest results from the SUPERB survey are due to be published in 2016.

### 3. Search Sensitivities & Completeness

At the time of preparing this contribution (early February 2016) there were \(N_{\text{FRB}} = 16\) FRBs in the literature\(^c\), covering the time period 2001 to 2014 inclusive. Although there are no FRBs yet known to have been detected in 2002 to 2008 inclusive this mostly reflects the fact that no large-scale wide-field pulsar/transient surveys were being undertaken at Parkes during that time. The FRB Catalogue (FRBCAT) has just been launched\(^d\) and should aid future work on population

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\(^a\)https://sites.google.com/site/publicsuperb/

\(^b\)http://sourceforge.net/projects/heimdall-astro/

\(^c\)https://github.com/ewanbarr/peasoup

\(^d\)http://astronomy.swin.edu.au/pulsar/frbcat/
characteristics as the numbers of FRBs grow. Indeed, one can already perform a number of important studies with the information stored in FRBCAT.

For example one can investigate the reported Galactic latitude dependence of FRBs\cite{47,48}. The observations seem to suggest a higher observed rate at high Galactic latitudes. If the intrinsic population is cosmological this might indicate the Galaxy is obscuring FRBs near the plane, but it is not clear what the cause might be\cite{47}.

We can perform a check, in analogy to ones performed in the early days of $\gamma$-ray burst studies: by determining dipolar and quadrupolar moments. The statistics $\langle \cos \theta \rangle$ and $\langle \sin^2 b - 1/3 \rangle$ should be Gaussian distributions centered at zero, for an isotropic distribution, where $\theta$ is the angle between the Galactic centre and an FRB, and $b$ is the Galactic latitude of the FRB. It is straightforward to show that with as few as 10 FRBs these statistics behave in their Gaussian limits, and as such their standard deviations are given by: $\sigma_{\langle \cos \theta \rangle} = (1/3N_{\text{FRB}})^{1/2}$ and $\sigma_{\langle \sin^2 b - 1/3 \rangle} = (4/45N_{\text{FRB}})^{1/2}$. From this simple test, it seems that the distribution of FRBs from Parkes is isotropic, but this quick comparison does not take a number of important completeness factors into consideration. For example this distribution must also be weighted by the total time spent on sky across all latitudes. Historically, a disproportionately large amount of time was spent searching the plane of the Galaxy, where the rate of pulsar discovery are highest. While some FRBs have been found at low Galactic latitudes\cite{25,56}, searches in other surveys specifically covering the Galactic Plane region have been unsuccessful at finding new bursts\cite{47}.

The combination of number of bursts and total time on sky will ultimately be the only reliable way of interpreting the total FRB rate and determining the degree of isotropy of the detected bursts. However, given the small sample currently available even a proper consideration of the corrections above prevents one from drawing a firm conclusion. A significant increase in the total population will be essential.

Moreover, detector-dependent selection effects also play an important role in the detectability of FRBs, not only at different telescopes but also for bursts with different widths and total dispersion measures. Recent works have shown\cite{26} that the algorithms used in some single pulse search codes can cause FRBs in the data to be missed, or their signal-to-noise ratio to fall below the threshold for a candidate event to be positively flagged by the search codes. In combination with other selection effects – such as the preferential sensitivity of many searches to pulses with narrower widths\cite{26} and a suspected reporting bias in the Galactic plane\cite{27} – that means that many surveys are not equally sensitive to all kinds of FRB pulses. A large enough sample of FRBs observed from different telescopes and backends is needed in order to constrain the severity of these effects.

4. The Future

At present the discovery rate at Parkes, with the typically available time-on-sky, is $\sim 5$ FRBs per year. This rate may be much higher if more dedicated search time is available, such as the planned use of the telescope for the Breakthrough Listen
initiative, which will be sensitive to dispersed radio pulses. During the lifetime of this project, over the next \( \sim 5 \) years, it is in principle possible to perform FRB searches commensally with pulsar timing and SETI searches so as to increase the time on sky. Longer term plans to put a PAF at the focus of the Parkes telescope may play into the selection effects discussed above, as using the current generation of PAFs necessarily sacrifices sensitivity for field of view. While increased field-of-view will certainly be beneficial, any reduction in sensitivity may mean only finding the brightest (and/or lowest redshift) of the events, perhaps hindering understanding of the population in its entirety.

The current population of FRBs already offers a rich and exciting field of study. The 16 published events to-date have a variety of properties and features and future discoveries hold great promise. As new instruments come on-line to search for FRBs in the coming years the population is expected to grow rapidly. Robust population studies should be possible within the next five years and many aspects of the FRB mystery may be solved in that time. Parkes remains a premiere instrument for FRB searching. In fact, advances in survey strategy and data processing have secured the SUPERB survey a leading role in this field in the near future. In particular, almost real-time detections in the SUPERB survey will enable us to answer the critical questions as to the origins of FRBs, their distribution throughout the Universe, and their usefulness as physical probes.

Ultimately, the future of FRB searches lies with the Square Kilometer Array (SKA). Searches with SKA1-MID are expected to yield several FRBs per week and, much like the Swift telescope did for GRBs, bring us into an era of regular real-time discovery. FRBs have never been detected below 700 MHz, but if indeed they are visible at lower frequencies SKA1-LOW will also be a powerful tool for providing discoveries and for understanding the FRB population.

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