Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
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Fast Radio Bursts: neutron stars, magnetars or something else?

Michael Kramer

MPI für Radioastronomy, Auf dem Hügel 69, 53121 Bonn, Germany
email: `mkramer@mpifr.de`
Jodrell Bank Centre for Astrophysics, University of Manchester
Oxford Road, Manchester M13 9PL, UK
email: `michael.kramer@manchester.ac.uk`

Abstract. Fast Radio Bursts (FRBs) are millisecond-long bursts of radio emission of extragalactic origin. The nature or FRBs is still unknown. Whether all FRBs are representatives of the same source population, or whether multiple underlying populations exist, is also unknown. One class that stands out is that of the "repeaters", i.e. FRBs from which multiple bursts have been detected. In these cases, appropriate models should be non-cataclysmic but yet being able to create powerful coherent radio emission. Magnetars are among those source types that are considered as possible explanation for (repeating) FRBs. This review will summarise the basic properties of FRBs and those of magnetars to provide a critical assessment of the possible physical connection between these classes of sources. We conclude that while magnetars may indeed be related to the FRB phenomenon, it is unlikely that they explain all FRBs, i.e. at least two classes of FRBs exist.

Keywords. stars: neutron, magnetars; transients: fast radio bursts

1. Introduction

In 2007, Lorimer et al. 2007 discovered a bright millisecond-long burst from a position on the sky near the Small Magellanic Cloud in archival pulsar search data. It was not until the work by Thornton et al. 2013 that was realised that these radio bursts are common, appearing across the sky typically every 10 seconds or so†, and that they are of truly extragalactic origin. Thornton et al. also introduced the name "Fast Radio Bursts" for the first time, which has been used ever since.

Meanwhile, the topic of FRBs has become a vibrant and exciting research field on its own. It is a fascinating topic for two reasons. Firstly, the nature of these FRBs is still not known. Do they all share the same origin? Or, are there different types? Secondly, FRBs have a cosmological origin and may, hence, be used as a cosmological probes. The latter includes the possibility to study the intergalactic magnetic field, the baryon content of the Universe and the nature of Dark Matter and Dark Energy or the ionisation history. (See, for instance, Macquart et al. 2015; Keane et al. 2016; Macquart et al. 2020; Caleb et al. 2019b for more details.) The former questions are more difficult to answer. As in other areas earlier, such as pulsars, the observational progress has outpaced the theoretical understanding. However, it is clear that magnetars (see e.g. Kaspi & Beloborodov 2017 for a review) are an attractive possibility to explain some (if not, many) of the observed FRB properties. This review is trying to provide an overview of such a comparison and a critical assessment.

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† This statement obviously depends on the sensitivity of the observations.

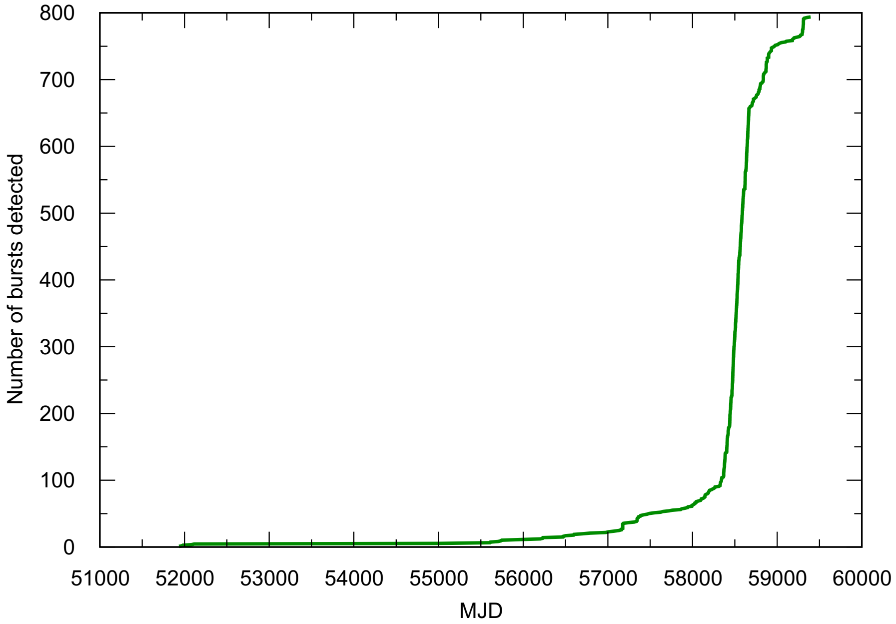

Figure 1. Number of known FRB bursts as a function of time. Currently, nearly 800 bursts of more than 600 FRBs are known.

Obviously, this review – and the comparison of source properties – is not going to be complete and will, probably, be soon outdated! The research field is so active, with a lot of more data collected every day, that the review cannot do justice to the many ongoing developments. In order to do so, one would need to

- keep track of the rapidly growing field of Fast Radio Bursts, both on observationial as well as on the theory side,
- provide a complete review of the properties of radio-loud magnetars
- provide details on pulsar (and magnetar) magnetospheric physics and the possible pulsar emission features.

This is beyond the scope here. For one, it is not be possible to mention every important FRB result so far, and also, the selection of information is probably not free from personal bias. Consequently, the drawn conclusions are biased by my own personal opinion and the reader may perhaps disagree with some of them.

2. FRBs - a brief history

In the following, I recall briefly the development of the field, before I summarise the properties that are relevant for a comparison to radio magnetars. For a much more detailed summary and discussion of FRBs properties and models, I recommend the recent reviews by Cordes & Chatterjee 2019; Petroff et al. 2019 and Caleb & Keane 2021.

Since the discovery by Lorimer et al. 2007 and the realisation by Thornton et al. 2013 that there is a whole population of FRBs, new telescopes and dedicated efforts have increased the number of detected FRBs enormously. Figure 1 shows the number of known bursts as a function of time. The large increase around MJD 58500 marks the large number of FRBs discovered by the CHIME experiment (Amiri et al. 2021). Being able to re-observe the same spot of the sky in regular intervals as done by CHIME also enables the detection of many more "repeating FRBs".

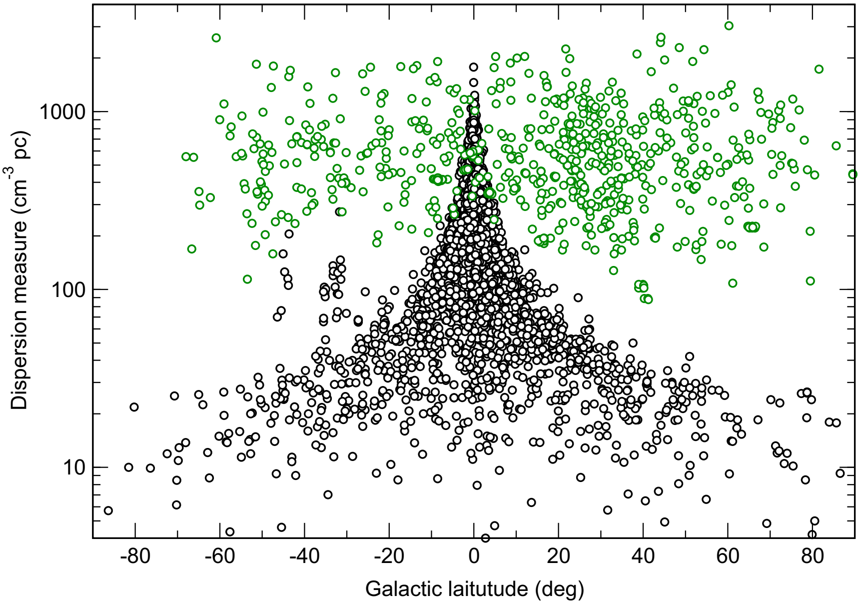

Figure 2. The dispersion measure (DM) of the detected FRB bursts as function of Galactic latitude. The DM distribution of FRBs (green) is clearly very different than that for pulsars (grray). The DM of most FRB is incompatible with a Galactic origin.

The first repeating FRB was discovered with the Arecibo telescoe by Spitler et al. 2016, indicating immediately that models for FRBs must include such of non-cataclysmic nature. Previously, only single bursts from a given FRB had been detected, despite long observing times in order to identify repeated signals. The question as to whether all FRBs eventually repeat is an important part of forming and identifying FRB models. Hence, we will return to this question in Section 3. At the moment, 24 repeaters are known, comprising less than 5% of the total population. †

The ability of organising VLBI experiments for repeating FRBs facilitates the identification of host galaxies (Chatterjee et al. 2017) although other methods have also proven to be successful, even for non-repeating FRBs (Bannister et al. 2019). At the time of writing, 19 FRBs could be associated with a host galaxy. The closest FRBs has been identified with a location in a globular cluster of the galaxy M81 (Kirsten et al. 2021a) The largest redshift of an identified host, $z = 0.66$, proves the suitability of FRBs for cosmological studies. The cosmological origin of FRBs was already established by Thornton et al. 2013, based on the dispersion measures (DM) of the discovered FRBs. The DM is the integrated column density of the free electrons along our line-of-sight. In the Milky Way, it is dominated by the ionized interstellar medium and combined with electron density models, the DM provide a distance estimate. In contrast, the DM of FRBs is significantly larger than the amount of electron “available” in the Galaxy, as shown in Figure 2. Hence, the DM is the sum of contributions from the Milky Way, the intergalactic medium, the host galaxy and potentially contributions local to the DM. Among the identified host galaxies a variety of types is found, and we refer to the aforementioned reviews for further details.

3. Basic FRB properties

The emission of FRBs is short in duration, typically a few or some tens of millisecond long. The short duration suggests that the emission may be beamed. With the beaming

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† See : `https://www.herta-experiment.org/frbstats/` for updated statistics.

angle being unknown, the implications on the energetics or the population numbers and detection rates are difficult to study. Nevertheless, the large distances suggest a very energetic process. It is not uncommon for FRBs to be highly polarised and the brightness temperatures implied by the pulse structures are of the order of 10^{36} K or more (see e.g. Cordes & Chatterjee 2019). At least in the case of repeating FRBs, the process creating FRBs cannot be cataclysmic. In this case, population numbers in order to explain the estimated rates, typically a few thousands per day and sky, can be less than required otherwise. The variety of host environments does not yet offer a clue as to whether one needs to look at a young or old population of sources.

Already early-on FRB have been suspected to be related to magnetars (see e.g. Camilo et al. 2006; Eatough et al. 2013) and a recent outburst of a Galactic magnetar, SGR 1935+2154, that showed some FRB-like properties (see Bochenek et al. 2020; CHIME/FRB Collaboration et al. 2020; Kirsten et al. 2021b), lends credence to such association. Nevertheless, a number of important questions remain (see e.g. Beloborodov 2021). In order to explore this possibility, we compare the FRB properties to those of magnetars, and also young pulsars. One has to take into account, however, that some of the emission properties may be the result of propagation effects, possibly happening near the source, but probably not directly at burst origin.

Based on the CHIME FRB catalouge, Pleunis et al. 2021 identified four archetypical types of bursts: a) Simple bursts comprised of one peak with a limited spectrum power-law, b) narrow-band simple bursts with a Gaussian-like spectrum, c) complex bursts with multiple peaks and similar (broad/narrow) frequency extent, and d) complex bursts with multiple sub-bursts that show a downward drift in frequency as time progresses. The first two groups make up 90% of the whole population (i.e. 30% and 60%, respectively). The last two groups make up 5% each. Repeaters are typically part of the last group, and it is interesting that this is consistent with making up about 5% of the detected population in general. It is important to emphasize that none of the observed spectra (i.e. in neither group) is consistent with the radio spectrum of magnetars or pulsars. The only similarity exits, perhaps, with the spectral properties of giant pulses in the Crab pulsar (see below). At the time of writing, there has been no published detection of FRBs below 100 MHz (e.g. with LOFAR or MWA), while the highest frequency of FRB detection is about 8 GHz with the GBT and Effelsberg.

It is notable that the emission properties of repeaters appear to be different from those of other FRBs. The downwards drift in frequency and a sub-dividing structure in the frequency-time plane is peculiar. Pleunis et al. 2021 also showed that bursts of repeaters are typically wider in time but narrower in bandwidth. These statistically significant differences may cast doubt on the possibility that all FRBs eventually repeat. So far, studies based on detection rates, such as those by Caleb et al. 2018, 2019a or James et al. 2020, are inconclusive. However, based on the emission properties the existence of (at least) two classes of FRBs appears plausible.

Apart from the burst shape and the peculiar frequency structure, also the polarisation properties seem to be different for repeating FRBs, though the picture is less clear here. There appears to be tendency for repeaters to be highly polarised with flat position angles and neglibile circular polarisation, see e.g. FRB 20121102A (Michilli et al. 2018) or FRB 20201124A (Hilmarsson et al. 2021). However, other observations of FRB 20201124A paint a more complicated picture, as the polarisation properties appear to be a function of frequency (Kumar et al. 2021). In contrast, non-repeaters are often less polarized, but also sometimes with significant circular polarisation. Interestingly, the rotation measure is large, as for the Galactic centre magnetar (Desvignes et al. 2018). Not only for this reason, it is intersting to compare those properties with those of radio-loud magnetars.

4. Radio-loud magnetars

After the initial discovery of transient radio emission of XTE J1810−197 by Camilo et al. 2006, four other magnetars have been studied via their transient radio emission: PSR J1550−5418 (Camilo et al. 2007), PSR J1622−4950 (Levin et al. 2010), the Galactic Centre magnetar PSR J1745−2900 (Eatough et al. 2013), PSR J1818−1607 (Champion et al. 2020) and SGR J1935+2154 (Bochenek et al. 2020; CHIME/FRB Collaboration et al. 2020; Kirsten et al. 2021b). These studies reveal a rather consistent picture of the radio emission properties of magnetars:

Magnetars, when detected in the radio, show a variable but flat flux density spectrum that is even inverted sometimes (Lazaridis et al. 2008; Caleb et al. 2022). The flatness of the spectrum has allowed us to detect pulsed radio emission of magnetars at frequencies as high as 353 GHz (Torne et al. 2022). The emission of magnetars is highly, often nearly 100%, linearly polarized, with a varying, sometimes complex swing of the position angle (see e.g. Kramer et al. 2007; Champion et al. 2020). The individual pulses consist of narrow, spiky emission structures, forming average pulse shapes that change often dramatically with frequency and time (see e.g. Kramer et al. 2007; Eatough et al. 2013; Dai et al. 2019 or Champion et al. 2020).

These features bear some resemblance to those of repeating FRBs, even though the spectral shape is clearly different. However, the association with magnetars is observationally supported by an detection of a FRB-like bursts from SGR J1935+2154 (Bochenek et al. 2020; CHIME/FRB Collaboration et al. 2020; Kirsten et al. 2021b). Here, the frequency structure of the few bursts detected also look rather different from those of other magnetars. A multi-frequency study (Bailes et al. 2021) constrained the distance to SGR J1935+2154 to be between 1.5 and 6.5 kpc. The upper limit is consistent with some other distance indicators and suggests that the recent bursts is closer to two orders of magnitude less energetic than the least energetic FRBs.

5. Structure and periodicities in FRBs

Recent high-time resolution observations of FRB 20180916B by Nimmo et al. 2021b have detected four highly linearly polarized bursts that show evidence of circular polarisation. As discussed before, the position angle swing of this repeater appears to be flat but at the highest resolution some modest variations are seen. Similar observations with even higher time resolution of FRB 20200120E by Majid et al. 2021 and Nimmo et al. 2021a have resolved isolated shots of emission shorter than 100 ns. These emission structures seem to be similar to the nano-shots seen for the Crab pulsar where the pulses also show some peculiar frequency structures (see e.g. Eilek & Hankins 2016). It is possible that these observations establish a general link between FRBs, young neutron stars and/or magnetars. However, this raises also the question as to whether these very short emission structures are common for FRBs or are, in fact, rare. Further observations are needed to answer this question.

On somewhat larger timescales, the CHIME collaboration (The CHIME/FRB Collaboration et al. 2021) reported the detection of sub-second periodicities in three FRBs, i.e. in FRB 20191221A (216.8 ± 0.1 ms), FRB 20210206A (2.8 ± 0.1ms) and FRB 20210213A (10.7 ± 0.1 ms).

On even longer timescales, the activity window of two repeating FRBs also shows a periodic occurrence, namely FRB 20180916B with a period of 16.4 ± 0.2 days (Chime/Frb Collaboration et al. 2020) and FRB 20121102A with a period of ~ 160 days (Rajwade et al. 2020; Cruces et al. 2021). Interestingly, there is no evidence for

Table 1. Comparison of FRB and magnetar emission features.

Feature	Verdict	Comment
Luminosity	not similar	Effects of luminosity function or beaming unknown
Spectra	not similar	Indication of propagation effects? See also Crab pulsar.
Polarisation	similar	All effects seen in magnetars (and pulsars and millisecond pulsars) are also seen
Burst structure	similar	Similar sub-structures and pulse features seen

periodicities between 1 ms and 1000 s in the extremely well studied case of the original repeating FRB (Li et al. 2021).

Obviously, a coherent picture still has to emerge. Whether these are timescales caused by the emission process, by a physical behaviour of the FRB as an object with or by the influence of an extrinsic force (e.g. a binary motion or precession), remains to be seen.

6. Comparing FRBs and magnetar properties

Having summarized the basic properties of both FRBs and magnetars, we will now assess how the various properties compare.

In terms of luminosity, the currently observed magnetar luminosities are barely sufficient to be consistent with FRBs. But it is possible that we only observe the top end of a broad luminosity function. Furthermore, the effects of an unknown beaming mechanism may further complicate the picture.

The spectra of FRBs are not consistent with those of magnetars. Propagation effects in medium near the FRBs may play a role. Moreover, the Crab pulsar provides an example of a young neutron star where the radio emission also emits some peculiar features not seen in other pulsars (or magnetars).

The polarisation properties are very similar for FRBs and magnetars. The agreement is better for repeating FRBs, but similarities also exist with the polarisation properties of pulsars in general, including the flat position angle often seen in millisecond puslars (Lorimer & Kramer 2005).

The burst shapes are similar to those of magnetars or pulsar. Also the sub-pulse structure is similar. Even the spiky emission features seen in some magnetars (e.g. Kramer et al. 2007) appear now to be seen also in observations of FRBs with sufficiently high resolution.

These findings are summarised in Table 1.

7. Personal Summary & Conclusions

We have seen that among FRBs there are distinct differences in their properties. The clearest differences exist between repeating FRBs and those that are currently not seen to repeat. This observational result strongly suggests that repeating FRBs are somewhat different and that there are ultimately (at least) two types of FRBs. In other words, I believe that the question as to whether all FRBs eventually repeat, is probably ‘no’.

The existence of at least two underlying populations would make the overall numbers of FRBs easier to explain. At the same time, the emission features of repeating FRBs are largely consistent with those of magnetars. This would imply the presence of large magnetic fields and potentially long rotational periods.

It is possible that circum-neutron star media will modify the observed emission properties but some imprint from magnetospheric physics will mostly likely remain. Models like those of Metzger and co-workers (see e.g. Metzger et al. 2022) reflect similar thoughts.

It will be exciting to see how these thoughts and models will fare with the many new discoveries and insight that will undoubtedly await us. It is going to be exciting.

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