SF2A 2021
A. Siebert, K. Baillié, E. Lagadec, N. Lagarde, J. Malzac, J.-B. Marquette, M. N'Diaye, J. Richard, O. Venot (eds)

A MAZE IN(G) FRB MODELS

G. Voisin[1]

Abstract. For a substantial part of FRB history, the number of FRB models could easily rival the count of the recorded events. Although this has changed in the last few years with the arrival of new instruments and the multiplication of observation campaigns which, on the one hand, have dramatically increased the number of events, and on the other hand have reduced the number of viable models, there remains a quite amazing diversity of ideas and mechanisms. I will attempt to gather in some broad categories the current state of the art, and focus more particularly on those model that predict possible repetitions and, in some cases, periodicity.

Keywords: Stars: neutron, (Stars:) pulsars: general, Stars: magnetars, Stars: flare, Radio continuum: general

1 Introduction

The topic of this review are the so-called fast radio bursts (FRB). These are short bursts, lasting typically 1 - 100 ms, that have been observed from $\sim$ 100MHz (LOFAR) to few GHz (Effelsberg) in radio frequency. Their dispersion measure, that is the column density of free electrons encountered by the signal on its way, indicates an extra-galactic and even cosmological origin (except for one source known in our Galaxy). The extra-galactic origin has been confirmed by the association of a dozen sources with host galaxies (Bochenek et al. 2021). As a result, the source must be intrinsically extremely bright, with isotropic equivalent luminosities in the range of $10^{38} - 10^{46}$ ergs/s (Bochenek et al. 2020; Lu et al. 2020), peak spectral luminosity $10^{28} - 10^{36}$ erg/Hz (Bochenek et al. 2020) (see Fig. 1, left) and brightness temperature well in excess of 10^{30}K (Bochenek et al. 2020), implying a coherent radiation mechanism.

This paper focuses on these FRB sources that have been seen to repeat. Indeed the majority of known FRB sources gave (so far) single events*. Whether this results from two distinct classes of sources, or simply from the fact that some sources repeat much more often is unknown. However, there are indications that repeaters have distinctive spectro-temporal characteristics, which might be key to select the correct FRB model(s).

Thus, repeaters usually show narrow spectral occupancy (Kumar et al. 2020) i.e. $\Delta f \sim f/N$ where f is frequency and $N \sim$ a few, downward-drifting sub-pulses (e.g. Hessels et al. 2019) i.e. a sequence of a few pulses the frequency window of which drifts to lower frequencies (see Fig. 1, right). Substructures on the scale of $\sim 10\mu s$ have also been observed (e.g. Farah et al. 2018; Cho et al. 2020; Nimmo et al. 2020). Repetitions appear to follow a clustered, non-poissonian distribution in time (Connor et al. 2016; Lawrence et al. 2017), although it has been argued that the distribution may be poissonian if the analysis is restricted to active windows (Cruces et al. 2021). Note that these statistical considerations follow essentially from one source, FRB121102, which is the most frequent repeater thus far. Periodic activity windows have been evidenced in two sources, FRB160916 and FRB121102, with periods of $\sim$ 16 and $\sim$ 160 days, and duty cycle ~ 0.3 and ~ 0.5 respectively (see Collaboration et al. (2020) and Rajwade et al. (2020); Cruces et al. (2021) respectively). Polarisation of the signal is very highly linear (e.g. Michilli et al. 2018; Hilmarsson et al. 2021). No counter-part have so-far been detected, with the exception of the Galactic source FRB200824 (Bochenek et al. 2020), which was accompanied by X-ray flares of the associated magnetar. Rotation measure (RM), which measures the integral of the magnetic field parallel to the line of sight, has no clear trend: some are compatible with a RM

[1] LUTH, Observatoire de Paris, PSL Research University, CNRS, 5 place Jules Janssen, 92195 Meudon, France
*See the FRB catalog at `https://www.wis-tns.org/` and CHIME/FRB repeater catalog `https://www.chime-frb.ca/repeaters`

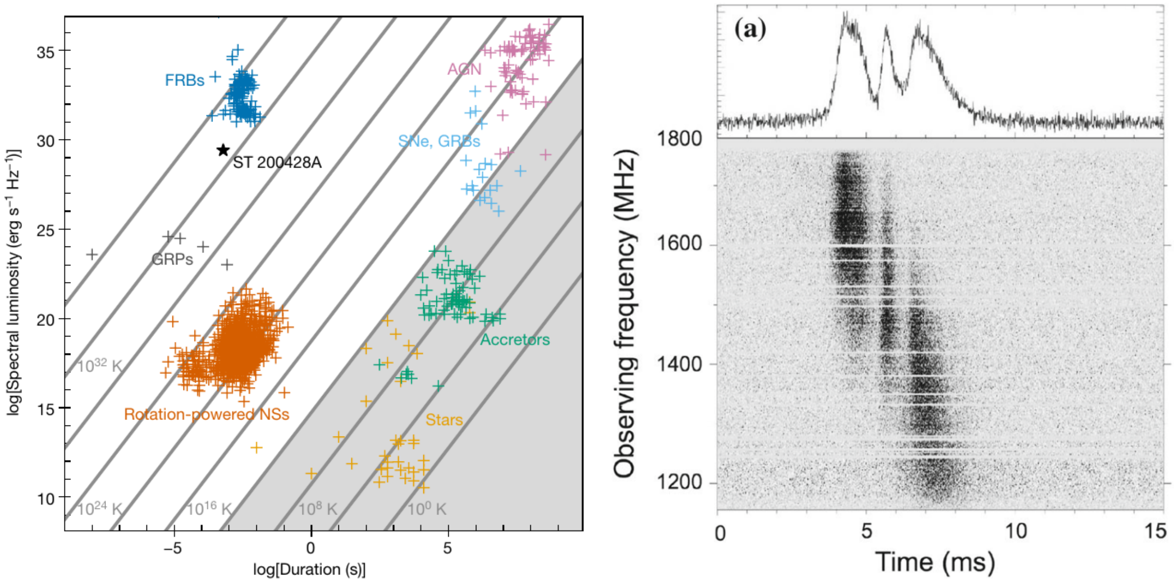

Fig. 1. Left: Equivalent isotropic spectral luminosity as a function of burst duration for sources in the centimetre-wavelength band. 'GRPs' stands for Giant Radio Pulses. ST 200428A correspond the burst from the galactic magnetar SGR 1935+2154, FRB200428, observed by STARE2. (more details in Bochenek et al. 2020). Right: An example of downward drifting subpulses from the loud repeater FRB121102 (from Hessels et al. 2019).

from the Galactic contribution alone or with a moderate intrinsic RM$\sim$ 200rad/m^2(Caleb et al. 2018), but we may note that the FRB121102 displays a very large value of $\sim 10^5$rad/m^2 (Michilli et al. 2018) which suggests a peculiar environment. Polarisation swing, the variation of polarisation angle through a burst, appears to be flat in most repeaters (e.g. Michilli et al. 2018; Hessels et al. 2019; Hilmarsson et al. 2021) with the exception of FRB180301 (Luo et al. 2020).

Currently, it is noteworthy that most modelling works focus on the characteristics of essentially three sources which we have already mentioned above. FRB121102 (Spitler et al. 2016, 2018; Josephy et al. 2019), which we may call the loud one due to the abundance of bursts observed, with sometimes 30 bursts/hour. It is also a particularly bright FRB, localised in a host galaxy 1Gpc away (Chatterjee et al. 2017; Tendulkar et al. 2017). It is also associated with a persistent radio counterpart (Marcote et al. 2017). It also has a periodic activity window spanning $\sim 60\%$ of the $\sim$ 160day period (Rajwade et al. 2020; Cruces et al. 2021).

FRB180916 (Collaboration et al. 2020; Pleunis et al. 2021), that we may call the periodic one, because it is the first one for which a periodic activity window has been observed. Due to its relatively short period, $\sim$ 16 days, it is better determined than the longer period of the loud FRB121102. Interestingly, recent LOFAR observations have shown that the $\sim$ 5-day activity window appears to start $\sim$ 3 days later in the LOFAR $100-190$MHz band than in the $400-800$Mhz CHIME/FRB band (Pleunis et al. 2021). It is located near a star-forming region in a galaxy 250Mpc away (Tendulkar et al. 2021; Marcote et al. 2020).

FRB200824, the Galactic one, is associated with magnetar SGR1935+2154 (Bochenek et al. 2020; Andersen et al. 2020). It is only known source of FRBs in our Galaxy. Only two consecutive bursts have been observed and it is therefore not strictly speaking a repeater. The bursts occurred during an X-ray outburst of the magnetar and are coincident with X-ray flares. Although it is somewhat dimmer than extra-galactic FRBs, it would be detected as such in a nearby galaxy, and is three orders of magnitude brighter than any other magnetar radio emission (see Fig.1). It is thus consistent with representing the low luminosity end of the FRB distribution.

The following focuses on models that involve a neutron star, usually a magnetar. These models represent the majority of the literature and are supported by the recent discovery of the Galactic FRB200428. Sec. 2 addresses models where the neutron star is necessary but not sufficient. One could see these models as challengers of the second category where magnetars are both necessary and sufficient, which we address in Sec. 3. In conclusion, Sec. 4, we direct the reader to other reviews that have been published in the recent years.

2 FRBs created by interaction of an object with a pulsar/magnetar

This category of models appeals to the interaction of neutron star with a third-party object, in particular asteroids. There are essentially two broad classes. In the first class, the energy powering FRBs comes from the neutron star magnetosphere/wind themselves, and an orbiting object is merely converting this energy into radiation. In the second class, the object is falling onto the neutron star and its gravitational energy is partly converted into FRBs. We see here why asteroids rather than larger objects can be appealing: it is easier to produce (frequently) repeating FRBs with small objects than with larger ones, as the number of objects can be larger, especially if the asteroids is destroyed in the process ! We note that in the current state of the literature these models appear as the main challengers, in terms of coarse bibliometric indicators, to the more discussed models where FRBs are produced by the neutron star alone (see Section 3).

2.1 Orbiting asteroid models

This model follows from the generalisation of a phenomenon known in the Solar system as Alfvén wings to the relativistic environment of neutron stars (Mottez & Zarka 2014). The source results from the interaction of an asteroid with the wind of a magnetar or a pulsar (Mottez et al. 2020; Decoene et al. 2020; Voisin et al. 2020). The object, immersed in the wind, forms a unipolar inductor and creates a plasma wake called Alfvén wings, because these perturbations are conveyed by Alfvén waves. As a result of the unipolar inductor phenomenon, a current flows along the wings and through the asteroid. Plasma instabilities may develop in the wings that convert the power carried by the current into coherent radiation through an unspecified mechanism. The available power is essentially limited by the wind power intercepted by the cross-section of the object, and modulated by a radio-conversion efficiency factor that one may take in the range $10^{-4} - 10^{-2}$ by analogy with similar phenomena in the solar system. An essential point is that, independently of the emission mechanism, the particles at the origin of the radiation are convected with the ultra-relativistic wind of the neutron star. As a result, any emission is highly collimated in a cone of apex $1/\gamma$, where γ is the Lorentz factor, which allows for bright pulses on a relatively cheap energy budget, visible at a large distance but unlikely to cross the line of sight of a nearby observer. Nonetheless, it has been shown that very young pulsars or magnetars (¡ 1000 years) are needed to provide sufficient power for distant FRBs such as the loud FRB121102 (Mottez et al. 2020). On the other hand, this mechanism should also produce fainter bursts with regular pulsar/magnetars.

One expects asteroids to be in belts or swarms, therefore one expects apparently random pulses every time an asteroid transits. Since the orbits of asteroids in such clusters is not strictly periodic due to many-body interactions and the very narrow beam of the emission one does not expect periodic repetition from a given asteroid. One caveat is that asteroid belts may reside too far from the source to produce strong enough FRBs. It has been proposed that asteroids may acquire very eccentric orbits thanks through Kozai-Lidov oscillations due to a distant black-hole companion(Decoene et al. 2020). In order to obtain a periodic active window, as seen in the repeater FRB180916, it has been proposed to cluster asteroids at 2:3 resonances of the orbit of a sub-stellar object (Voisin et al. 2020). A prediction of this model is that rare events may occur outside of the activity window.

2.2 Falling asteroids models

This model relies on the idea that a neutron star may occasionally cross an asteroid field surrounding a main-sequence star, which would provoke the collision of some asteroids with the neutron star, and FRBs (Geng & Huang 2015; Dai et al. 2016; Bagchi 2017; Smallwood et al. 2019; Liu et al. 2020; Dai 2020; Dai & Zhong 2020). Although the event is unlikely, these authors argue that it is sufficient to produce the observed FRB rate. An important element is that the neutron star should be a dead pulsar or magnetar rather than an active one, which considerably increases the reservoir of objects available (Geng & Huang 2015; Dai et al. 2016; Dai & Zhong 2020, e.g.). This is necessary to avoid evaporation of the asteroid by the intense high-energy radiations from the neutron star before it reaches the magnetosphere, which would prevent FRB production.

The scenario starts with an asteroid on a collision course with the NS. Past the Roche limit, the asteroid is torn apart into several pieces and continues its way until it reaches the magnetosphere. Each piece moving in the magnetic field of the neutron star creates a unipolar inductor electric field which locally accelerates electrons and positrons in the magnetosphere, producing coherent curvature radiation. The successive pieces may produce downward-drifting sub-pulses by the interplay of radius-to-frequency mapping Liu et al. (2020).

Coherent curvature radiation also explains the mostly linear polarisation seen in FRBs. The overall duration is connected to the size of the initial asteroid.

This mechanism may be adapted to produce periodic activity windows by assuming that the NS is in an eccentric orbit with a main-sequence star possessing a asteroid field. The NS then crosses the asteroid field when close enough to its periastron, and the width of the activity window is determined by the eccentricity of the orbit.

A variation of this model replaces the asteroid field+MS star by a white dwarf in an eccentric orbit around the NS. The white dwarf overflows its Roche lobe around periastron, and the material falls onto the neutron star similarly to asteroids. In order to produce the observed activity window, the material would have to reach very quickly (compared to the orbital period) the inner magnetospheric region of the NS, and it is unclear what may cause it to spiral so fast.

3 FRBs created from the magnetar/pulsar itself

The association of FRBs with magnetars is the most studied hypothesis in the literature. It was originally proposed by Popov & Postnov (2010) that a scaled-up version of magnetar flares might have a coherent radio counterpart visible at cosmological distances while the high energy component would be too faint for current instrumentation. To provide the necessary power, most (but not all, see below) models appeal to young magnetars with stronger magnetic and spin-down power. The abundance of such objects is sufficient to provide the observed FRB population (e.g. Metzger et al. 2017), possibly forming a rare sub-population of magnetars Lu et al. (2020); Margalit et al. (2020).

Interestingly, the theory of coherent radio counterpart to X-ray flares also originally followed from an analogy between type III solar flares and magnetars (Lyutikov 2002). Type III solar flares indeed associate X-ray emission with coherent radio emission with a fluence ratio of $F_R/F_X \sim 10^{-4}$. Such ratio has been observed in past radio emission from the galactic magnetar XTE J1810-197, and the recent observation of the Galactic FRB200428 seems to extend further this correlation, which therefore spans about 20 orders of magnitude (see Fig. 2, left). The accumulation of events, in particular from the loud FRB121102, allowed to compare the frequency and energy distributions of FRBs with those of magnetar bursts. This led some authors to argue in favour of the association between the two based on statistical similarity (e.g Wadiasingh & Chirenti 2020; Popov & Postnov 2010).

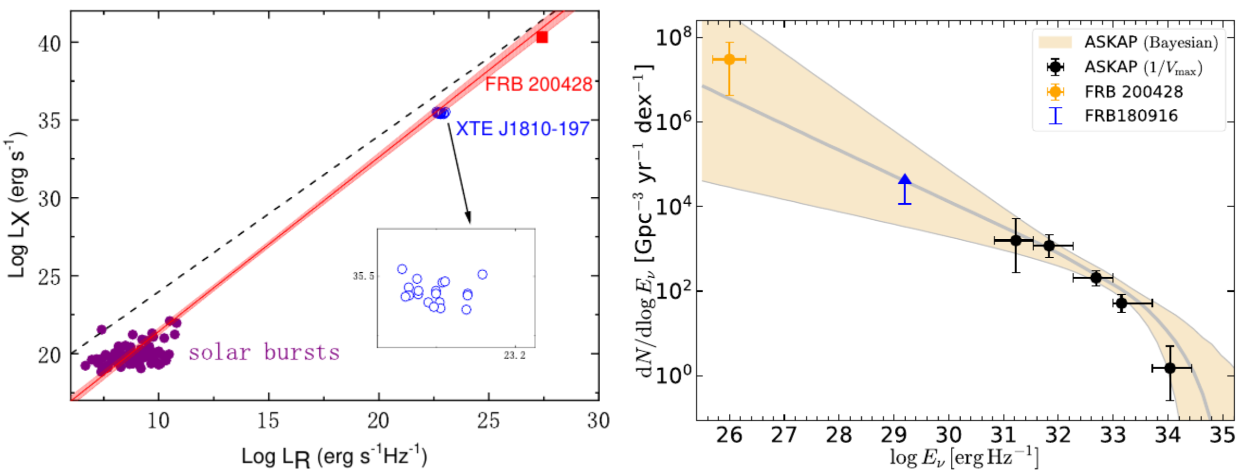

Fig. 2. Left: Relation X-ray vs radio isotropric equivalent luminosities of type III solar bursts, magnetar XTE J1810-197, and the Galactic FRB200428. The red line is a fit on this data. The dashed line is the Güdel-Benz correlation, which can only be used the gyrosynchrotron radio emissions, and does correspond to the data. (from Wang et al. 2021). Right: Volumetric rate of FRB events as a function of their specific energy E_ν (intrinsic energy released at frequency ν) at 1.4GHz. Black markers are ASKAP data. Orange marker is the Galactic FRB200428 observed by STARE2. Blue marker is a 90% confidence level lower limit on the contribution of the repeater FRB180916 derived from the CHIME/FRB data (Collaboration et al. 2020) (so at $\sim$ 600MHz instead of 1.4GHz). The silver lines show the mean and 68% confidence region of the bayesian fit performed on the ASKAP data alone (Lu & Piro 2019). (from Lu et al. 2020).

Energetically, one can show it is unlikely that rotation power suffices by itself, even for a very young pulsar (Metzger et al. 2017), which tends to discard this hypothesis and in particular the idea that FRBs would be a scaled-up version of the supergiant pulses of the Crab (Cordes & Wasserman 2016). On the other hand, dissipation of magnetic energy, as in magnetars (Thompson & Duncan 1996), appears to be sufficient even for normal magnetars (i.e. similar to the known Galactic objects) if efficiency is as high as $F_R/F_X \sim^{-2}$. Otherwise, decade to century old objects are needed. In the latter case, magnetar activity is expected to decrease measurably over a few years/decades, and DM/RM variations are expected from the young supernova remnant.

Practically, large bursts of energy are released by star-quakes, that is when the crust of the star, stressed by the huge magnetic field, eventually breaks releasing magnetic energy (Thompson & Duncan 1996). This in turn creates a large perturbation of the magnetosphere, eventually propagating into the wind zone†.

3.1 Magnetospheric models

These models assume that the radio emission is produced within the magnetosphere, and in this way they are the natural prolongation of the early papers on magnetar radio emission that pointed out a possible similarity to type III solar flares (Lyutikov 2002). It is indeed well established that the X-ray emission of Galactic magnetars comes from their magnetosphere, and therefore one may expect a putative radio counterpart to have the same origin. Recently, authors argued that the FRB rate from the Galactic FRB200428 was compatible with being the tail of the observed extragalactic FRB distribution (see Fig. 2, right). It follows from this argument that the Galactic FRB200428 is part of the same population of sources as other FRBs and, if one assumes magnetospheric radio emissions for magnetars, emissions of the general population are magnetospheric as well.

Several emission mechanisms have been proposed in the literature. The most commonly found is undoubtedly bunched curvature radiation, whereby bunches of electrons or positrons moving relativistically along field lines in the magnetosphere emit coherently provided that they share a common location both in position and velocity space. This mechanism has been recently shown to be able to provide a wide range of luminosities, from pulsars to FRBs (Cooper & Wijers 2021). However, this has also been criticised as an overly simplistic view of the plasma behaviour (Lyubarsky 2021), since it remains unclear how such coherent bunches could form, the model being being effectively a coherent addition of individual particle motion, and not a collective mode of the plasma. These authors advocate fast magnetosonic waves to convey the energy released in the star quake through the magnetosphere, arguing that such waves can eventually escape the magnetosphere. Other authors (Kumar & Bošnjak 2020) argue in favour of large-amplitude Alfvén waves conveying the energy outward until the plasma density is insufficient to sustain these waves. They then break into particle bunches radiating under the coherent curvature radiation mechanism. Some authors (e.g.) only refer to the pulsar emission mechanism, thereby assuming that the same mechanism that produces coherent emission responsible for pulsar radio emissions is likely to function as well in magnetars.

In this picture, the duration of a burst is naturally scaled with the magnetosphere light-crossing time, which is of the order of the millisecond. The occupied frequency band is not necessarily narrow, except if one relies on the Solar flare analogy (Lyutikov 2002), since type III flare have narrow spectral occupancy. However, the magnetosphere is particularly favourable to the phenomenon of radius-to-frequency mapping whereby emission frequency is connected to the altitude (or radius) of emission. This is due to the fact that all emission mechanisms scale either with the magnitude of the magnetic field or the radius of curvature of the local magnetic field (for curvature radiation) and both are monotonously decreasing with radius for simple magnetic geometry (e.g. dipole field). As a result, the spectral properties of the burst become geometric properties of the magnetosphere, similarly to the RVM model for radio pulsars (Radhakrishnan & Cooke 1969; Pétri 2017). Thus, by playing on the parameters of the magnetic field geometry, the line of sight, and the spin that makes the observer sweep through a given cross-section of the magnetosphere during a given burst, one can reproduce a broad range of temporal and spectral behaviours (Lyutikov 2020; Li & Zanazzi 2021). The sweep can also explain polarization swing.

In these models, an X-ray counterpart is expected with a luminosity ratio of $10^2 - 10^5$ compared to radio. This was seen for the Galactic FRB200428, but is undetectable with current instruments for extra-galactic sources. If future instruments were able to detect such counterparts, this would be a clear evidence in favour of the magnetar model. The fact that most X-ray bursts lack a radio counterpart may be interpreted in terms of

†In pulsars and magnetars, the wind zone is the zone beyond the light cylinder, while the magnetosphere is within. The light cylinder is the surface where an hypothetical plasma co-rotating with the star reaches the speed of light.

relative beaming Lu et al. (2020).

A variant is the low-twist magnetar model Wadiasingh & Timokhin (2019); Wadiasingh & Chirenti (2020); Wadiasingh et al. (2020). In this model, it is argued that the emission mechanism is the same as for pulsars. The originality is that, instead of appealing to young and powerful magnetars, this model appeals to old, slow stars. The argument is that old magnetars can have lower magnetospheric charge density unable to screen the onset of a highly efficient 'pulsar emission mechanism' when triggered by a star-quake pertubation.

3.2 Blast wave models

This model is derived from models for short gamma ray bursts (e.g. Lyubarsky 2014; Beloborodov 2017, 2020; Zhang 2020). It considers that, when a starquake occurs, its energy is conveyed through the magnetosphere by Alfvén waves, which eventually provoke magnetic reconnection near the light cylinder. Then, a plasmoid is ejected into the wind with a very high Lorentz factor, up to 10^5 (Beloborodov 2020). In addition, the wind is greatly enhanced during a quake episode due to intense magnetospheric perturbations, and a denser variable wind along with and a train of plasmoids may be produced. Some plasmoids may propagate at super-magnetosonic speeds within the previous ejecta and produce a strong shock wave. A cyclotron maser develops at the shock, responsible for coherent radio emission.

Emission is linearly polarized (e.g. Lyubarsky 2021), and weakly beamed due to the pancake-like shape of the plasmoid which occupies a broad solid angle as seen from the source while being relatively thin. Emission frequency scales with the local plasma frequency and therefore drops as the plasmoid propagates away from the star. It is argued that the duration of a burst at GHz frequency is compatible with a few milliseconds (Beloborodov 2017, 2020). Overall, FRBs should be seen in a wide frequency range, and an optical counterpart is expected in some models (Beloborodov 2020). So far optical follow-up observations gave only upper limits (Hardy et al. 2017; Tingay & Yang 2019; Kilpatrick et al. 2021).

3.3 Periodicity mechanisms

The intrinsic magnetar models summarised above predict repetitions without periodicity. We here examine present two additional complementary mechanisms compatible with the two observed periods.

Free precession results from the deformation of the star by the magnetic stress of the huge field of a magnetar (Levin et al. 2020; Zanazzi & Lai 2020). It is not so far observed in galactic magnetars, where it might be suppressed by superfluidity (Shaham 1977). Young magnetars, on the other hand, might be sufficiently hot to prevent superfluidity to set in, and allow precession with the required magnitude. One key prediction in this case is the rapid increase of the period over a few years.

In the frame of the low-twist model, for older magnetars, it has been proposed that periodicity might result from ultra-long spin periods (Beniamini et al. 2020).

Alternatively, it has been proposed that a magnetar might be in a close binary with a O/B star (Lyutikov et al. 2020). The wind of the companion enshrouds the magnetar, leaving only a relatively narrow corridor for radio emissions to escape the environment of the magnetar without excessive free-free absorption. Thus, the period is set by the orbit and the activity window by the width of the corridor. A key prediction is the variability of the activity window with frequency, due to the frequency dependence of absorption.

All three models have been suggested to explain the 3-day low-frequency lag of the repeater FRB180916 (Pleunis et al. 2021; Li & Zanazzi 2021).

4 Conclusions

A number of reviews on FRBs are a available in the literature. Let us mention the 'living theory catalog for fast radio bursts' (Platts et al. 2019)[‡] which is probably the most exhaustive listing of FRB models, including catastrophic events and non neutron-star scenarios. Observations are reviewed in particular in (Petroff et al. 2019, 2021). The review (Cordes & Chatterjee 2019) is probably the most advanced concerning propagation effects for FRBs. Let us use this opportunity to admit that propagation effects are one of the missing pieces of the current review, as this should be included in any model that aims at fully reproducing observations. There is also specialised review on emission mechanisms for FRBs, particularly related to blast waves and synchrotron masers (Lyubarsky 2021).

[‡]The catalog is available at `https://frbtheorycat.org/`.

References

Andersen, B. C., Bandura, K. M., Bhardwaj, M., et al. 2020, Nature, 587, 54, number: 7832 Publisher: Nature Publishing Group

Bagchi, M. 2017, The Astrophysical Journal, 838, L16, publisher: American Astronomical Society

Beloborodov, A. M. 2017, ApJ, 843, L26, _eprint: 1702.08644

Beloborodov, A. M. 2020, ApJ, 896, 142, _eprint: 1908.07743

Beniamini, P., Wadiasingh, Z., & Metzger, B. D. 2020, MNRAS, 496, 3390, _eprint: 2003.12509

Bochenek, C. D., Ravi, V., Belov, K. V., et al. 2020, Nature, 587, 59, bandiera_abtest: a Cg_type: Nature Research Journals Number: 7832 Primary_atype: Research Publisher: Nature Publishing Group Subject_term: Astronomical instrumentation;Compact astrophysical objects;High-energy astrophysics;Time-domain astronomy;Transient astrophysical phenomena Subject_term_id: astronomical-instrumentation;compact-astrophysical-objects;high-energy-astrophysics;time-domain-astronomy;transient-astrophysical-phenomena

Bochenek, C. D., Ravi, V., & Dong, D. 2021, The Astrophysical Journal Letters, 907, L31

Caleb, M., Keane, E. F., van Straten, W., et al. 2018, Monthly Notices of the Royal Astronomical Society, 478, 2046, aDS Bibcode: 2018MNRAS.478.2046C

Chatterjee, S., Law, C. J., Wharton, R. S., et al. 2017, Nature, 541, 58, aDS Bibcode: 2017Natur.541...58C

Cho, H., Macquart, J.-P., Shannon, R. M., et al. 2020, The Astrophysical Journal Letters, 891, L38

Collaboration, T. C., Amiri, M., Andersen, B. C., et al. 2020, arXiv:2001.10275 [astro-ph], arXiv: 2001.10275

Connor, L., Pen, U.-L., & Oppermann, N. 2016, MNRAS, 458, L89, _eprint: 1601.04051

Cooper, A. J. & Wijers, R. A. M. J. 2021, Monthly Notices of the Royal Astronomical Society, aDS Bibcode: 2021MNRAS.tmpL..84C

Cordes, J. M. & Chatterjee, S. 2019, Annual Review of Astronomy and Astrophysics, 57, 417

Cordes, J. M. & Wasserman, I. 2016, MNRAS, 457, 232, _eprint: 1501.00753

Cruces, M., Spitler, L. G., Scholz, P., et al. 2021, Monthly Notices of the Royal Astronomical Society, 500, 448

Dai, Z. G. 2020, ApJ, 897, L40, _eprint: 2005.12048

Dai, Z. G., Wang, J. S., Wu, X. F., & Huang, Y. F. 2016, ApJ, 829, 27, _eprint: 1603.08207

Dai, Z. G. & Zhong, S. Q. 2020, ApJ, 895, L1, _eprint: 2003.04644

Decoene, V., Kotera, K., & Silk, J. 2020, arXiv e-prints, 2012, arXiv:2012.00029

Farah, W., Flynn, C., Bailes, M., et al. 2018, arXiv:1803.05697 [astro-ph], arXiv: 1803.05697

Geng, J. J. & Huang, Y. F. 2015, ApJ, 809, 24, _eprint: 1502.05171

Hardy, L. K., Dhillon, V. S., Spitler, L. G., et al. 2017, Monthly Notices of the Royal Astronomical Society, 472, 2800, aDS Bibcode: 2017MNRAS.472.2800H

Hessels, J. W. T., Spitler, L. G., Seymour, A. D., et al. 2019, The Astrophysical Journal, 876, L23, publisher: American Astronomical Society

Hilmarsson, G. H., Spitler, L. G., Main, R. A., & Li, D. Z. 2021, publication Title: arXiv e-prints ADS Bibcode: 2021arXiv210712892H Type: article

Josephy, A., Chawla, P., Fonseca, E., et al. 2019, The Astrophysical Journal, 882, L18, aDS Bibcode: 2019ApJ...882L..18J

Kilpatrick, C. D., Burchett, J. N., Jones, D. O., et al. 2021, The Astrophysical Journal Letters, 907, L3

Kumar, P. & Bošnjak, Ž. 2020, Monthly Notices of the Royal Astronomical Society, 494, 2385

Kumar, P., Shannon, R. M., Flynn, C., et al. 2020, Monthly Notices of the Royal Astronomical Society, 500, 2525

Lawrence, E., Vander Wiel, S., Law, C., Burke Spolaor, S., & Bower, G. C. 2017, AJ, 154, 117, _eprint: 1611.00458

Levin, Y., Beloborodov, A. M., & Bransgrove, A. 2020, The Astrophysical Journal, 895, L30, aDS Bibcode: 2020ApJ...895L..30L

Li, D. & Zanazzi, J. J. 2021, The Astrophysical Journal, 909, L25, aDS Bibcode: 2021ApJ...909L..25L

Liu, Z.-N., Wang, W.-Y., Yang, Y.-P., & Dai, Z.-G. 2020, ApJ, 905, 140, _eprint: 2010.14379

Lu, W., Kumar, P., & Zhang, B. 2020, MNRAS, 498, 1397, _eprint: 2005.06736

Lu, W. & Piro, A. L. 2019, The Astrophysical Journal, 883, 40, aDS Bibcode: 2019ApJ...883...40L

Luo, R., Wang, B. J., Men, Y. P., et al. 2020, Nature, 586, 693, bandiera_abtest: a Cg_type: Nature Research Journals Number: 7831 Primary_atype: Research Publisher: Nature Publishing Group Subject_term: Compact astrophysical objects;Transient astrophysical phenomena Subject_term_id: compact-astrophysical-objects;transient-astrophysical-phenomena

Lyubarsky, Y. 2014, Monthly Notices of the Royal Astronomical Society, 442, L9

Lyubarsky, Y. 2021, Universe, 7, 56, number: 3 Publisher: Multidisciplinary Digital Publishing Institute

Lyutikov, M. 2002, The Astrophysical Journal Letters, 580, L65

Lyutikov, M. 2020, ApJ, 889, 135, _eprint: 1909.10409

Lyutikov, M., Barkov, M. V., & Giannios, D. 2020, The Astrophysical Journal, 893, L39, publisher: American Astronomical Society

Marcote, B., Nimmo, K., Hessels, J. W. T., et al. 2020, Nature, 577, 190

Marcote, B., Paragi, Z., Hessels, J. W. T., et al. 2017, The Astrophysical Journal Letters, 834, L8

Margalit, B., Beniamini, P., Sridhar, N., & Metzger, B. D. 2020, ApJ, 899, L27, _eprint: 2005.05283

Metzger, B. D., Berger, E., & Margalit, B. 2017, The Astrophysical Journal, 841, 14

Michilli, D., Seymour, A., Hessels, J. W. T., et al. 2018, Nature, 553, 182

Mottez, F. & Zarka, P. 2014, Astronomy and Astrophysics, 569, A86

Mottez, F., Zarka, P., & Voisin, G. 2020, Astronomy & Astrophysics, 644, A145, publisher: EDP Sciences

Nimmo, K., Hessels, J. W. T., Keimpema, A., et al. 2020, arXiv e-prints, 2010, arXiv:2010.05800

Pétri, J. 2017, Monthly Notices of the Royal Astronomical Society, 466, L73

Petroff, E., Hessels, J. W. T., & Lorimer, D. R. 2019, The Astronomy and Astrophysics Review, 27, 4

Petroff, E., Hessels, J. W. T., & Lorimer, D. R. 2021, Fast radio bursts at the dawn of the 2020s, Tech. rep., publication Title: arXiv e-prints ADS Bibcode: 2021arXiv210710113P Type: article

Platts, E., Weltman, A., Walters, A., et al. 2019, Physics Reports, 821, 1

Pleunis, Z., Michilli, D., Bassa, C. G., et al. 2021, The Astrophysical Journal Letters, 911, L3, publisher: American Astronomical Society

Popov, S. B. & Postnov, K. A. 2010, in Evolution of Cosmic Objects through their Physical Activity, ed. H. A. Harutyunian, A. M. Mickaelian, & Y. Terzian, 129–132, _eprint: 0710.2006

Radhakrishnan, V. & Cooke, D. J. 1969, Astrophysical Letters, 3, 225

Rajwade, K. M., Mickaliger, M. B., Stappers, B. W., et al. 2020, arXiv:2003.03596 [astro-ph], arXiv: 2003.03596

Shaham, J. 1977, The Astrophysical Journal, 214, 251, aDS Bibcode: 1977ApJ...214..251S

Smallwood, J. L., Martin, R. G., & Zhang, B. 2019, MNRAS, 485, 1367, _eprint: 1902.05203

Spitler, L. G., Herrmann, W., Bower, G. C., et al. 2018, The Astrophysical Journal, 863, 150, publisher: American Astronomical Society

Spitler, L. G., Scholz, P., Hessels, J. W. T., et al. 2016, Nature, 531, 202

Tendulkar, S. P., Bassa, C. G., Cordes, J. M., et al. 2017, The Astrophysical Journal, 834, L7, aDS Bibcode: 2017ApJ...834L...7T

Tendulkar, S. P., Gil de Paz, A., Kirichenko, A. Y., et al. 2021, The Astrophysical Journal Letters, 908, L12

Thompson, C. & Duncan, R. C. 1996, The Astrophysical Journal, 473, 322

Tingay, S. J. & Yang, Y.-P. 2019, The Astrophysical Journal, 881, 30, aDS Bibcode: 2019ApJ...881...30T

Voisin, G., Mottez, F., & Zarka, P. 2020

Wadiasingh, Z., Beniamini, P., Timokhin, A., et al. 2020, ApJ, 891, 82, _eprint: 1910.06979

Wadiasingh, Z. & Chirenti, C. 2020, ApJ, 903, L38, _eprint: 2006.16231

Wadiasingh, Z. & Timokhin, A. 2019, ApJ, 879, 4, _eprint: 1904.12036

Wang, F. Y., Zhang, G. Q., & Dai, Z. G. 2021, MNRAS, 501, 3155, _eprint: 1903.11895

Zanazzi, J. J. & Lai, D. 2020, ApJ, 892, L15, _eprint: 2002.05752

Zhang, B. 2020, Nature, 587, 45, number: 7832 Publisher: Nature Publishing Group