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## A MAZE IN(G) FRB MODELS

G. Voisin<sup>1</sup>

**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

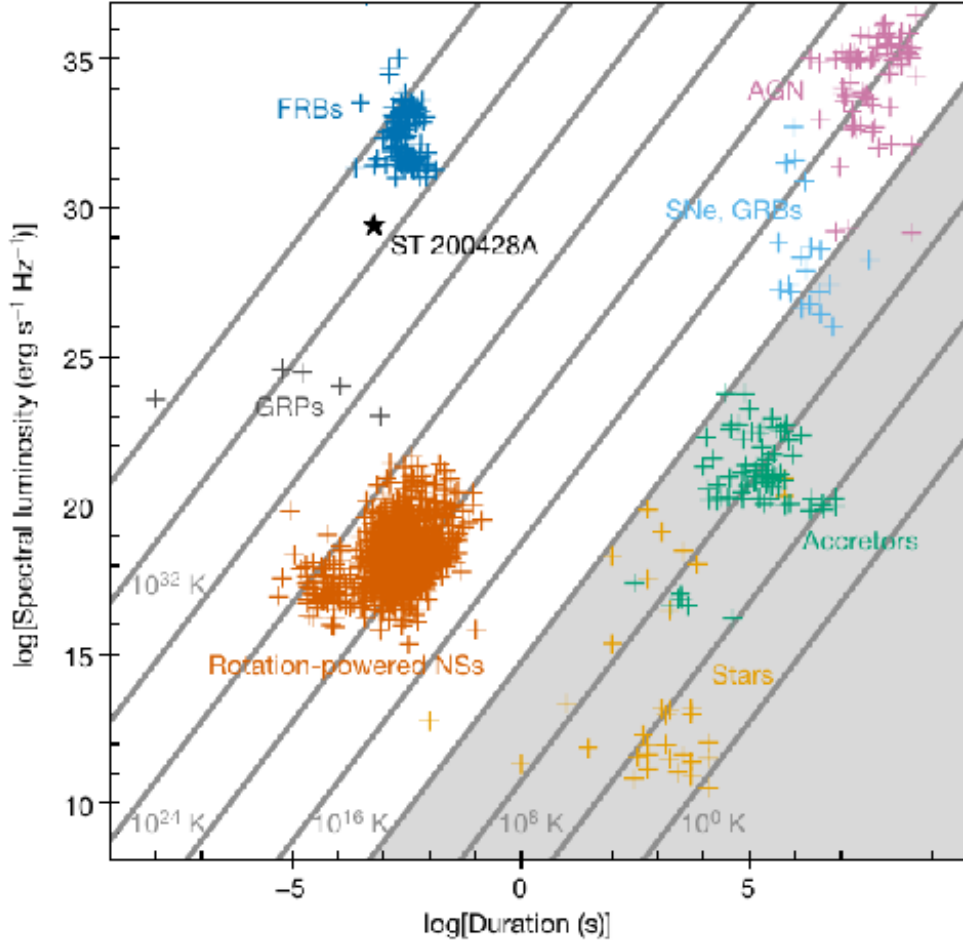
The field of fast radio bursts is one currently in rapid expansion, either from the observational or theoretical point of view. For this reason, the interested reader is urged to refer directly to the literature cited in this text and check for possible updates. For the same reason, I also included a certain number of papers still under review but available on preprint servers. The vision of the field proposed in this short review should be considered by no means complete.

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  $\sim 100$  MHz (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 with 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) and brightness temperature well in excess of  $10^{30}$  K (Bochenek et al. 2020), implying a coherent radiation mechanism.

In this review, we focus on these FRB sources that have been seen to repeat. Indeed the majority of known FRBs are (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 : 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. 2). Substructures on the scale of  $\sim 10 \mu$ s has also been observed (e.g. Farah et al. 2018; Cho et al. 2020; Nimmo et al. 2020). The 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). Periodic activity windows have been evidenced in two sources, FRB160916 and FRB121102, with periods of  $\sim 16$  and  $\sim 160$  days, and duty cycle  $\sim 0.3$  and  $\sim 0.5$  respectively (see Collaboration et al. (2020) and ?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

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\*See the FRB catalog at <https://www.wis-tns.org/> and CHIME/FRB repeater catalog <https://www.chime-frb.ca/repeaters>



**Fig. 1.** 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).

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 measure the integral of the magnetic field parallel to the line of sight, has no clear trend: some are compatible with a RM from the Galactic contribution alone or with a moderate intrinsic  $\text{RM} \sim 200 \text{ rad/m}^2$  (?), but we may note that the FRB121102 displays a very large value of  $\sim 10^5 \text{ rad/m}^2$  (Michilli et al. 2018) which suggests a peculiar environment. Polarisation swing, the variation of the polarisation angle through the burst, appears to be flat in most repeaters (Michilli et al. 2018; ?; Hilmarsson et al. 2021, e.g.) with the exception of FRB180301 (Luo et al. 2020).

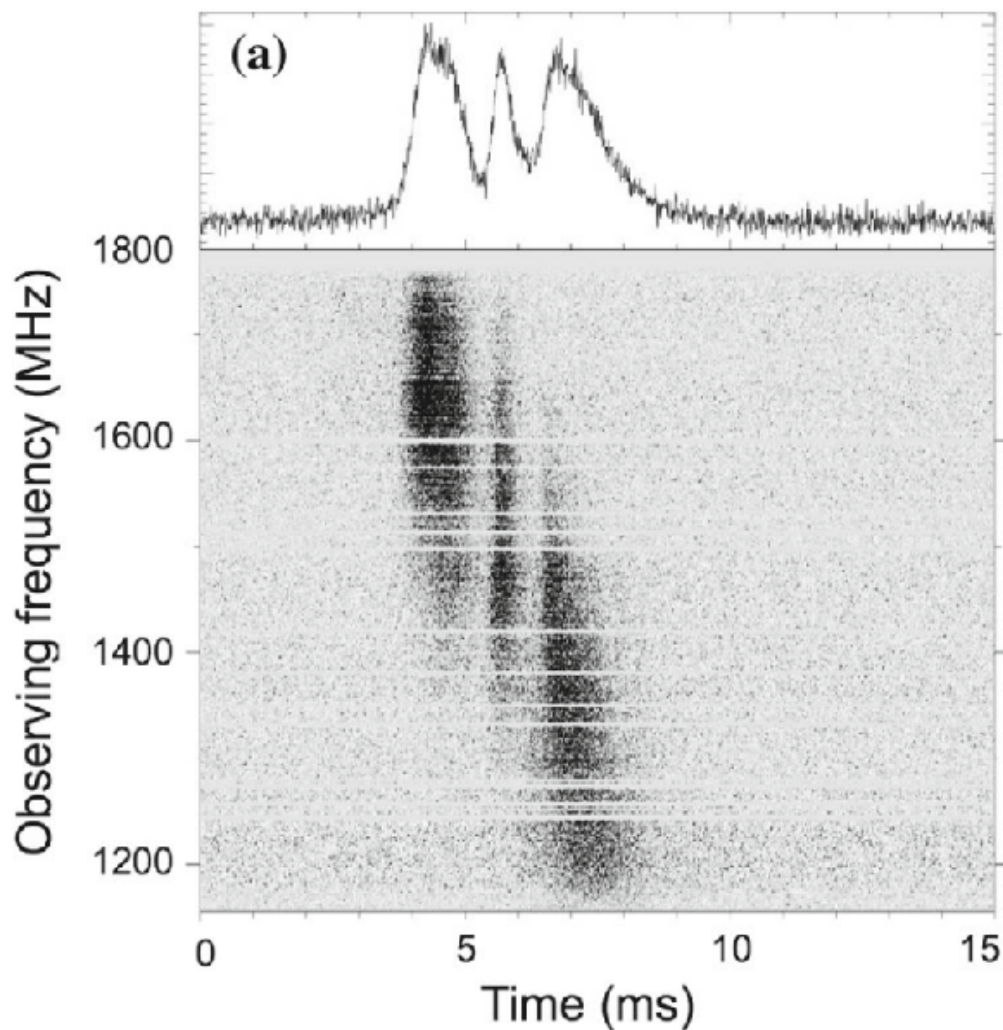
Currently, it is noteworthy that most modelling works focus on the characteristics of essentially three sources which we have already mentioned above. FRB121102 (Spitler et al. 2016, 2018; ?), which we may call the loud one due to the abundance of bursts observed, with sometimes 30 bursts/hour. It is 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).

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 – 190MHz band than in the 400 – 800MHz 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). 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 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. 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 other category where magnetars are both necessary and sufficient, which we address in Sec. 3. In conclusion, we direct the reader to other reviews that have been published in the recent years.



**Fig. 2.** An example of downward drifting subpulses from the loud repeater FRB121102 (from Hessels et al. 2019).

## 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  $\gamma$  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 (j 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.

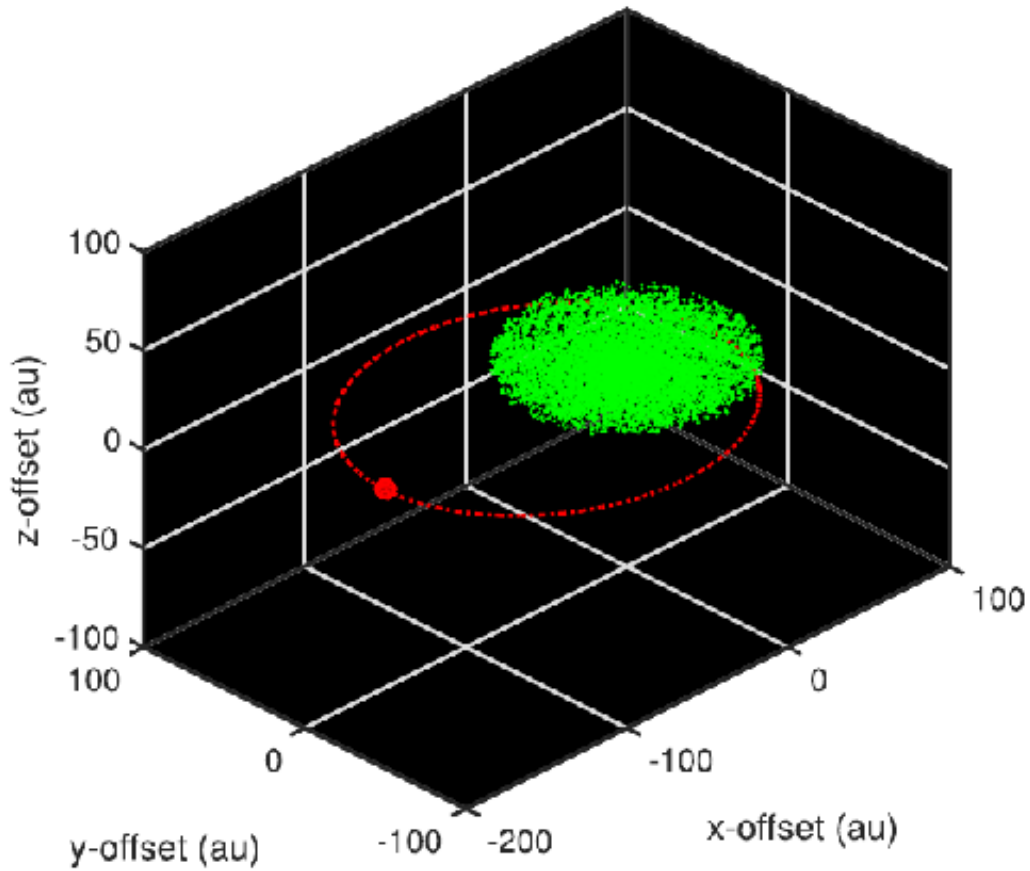
### 2.2 *Falling asteroids models*

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 (see Fig. 3 ). 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



**Fig. 3.** A configuration allowing for periodic activity windows in the falling asteroid model. An old neutron star, in red, is in an eccentric orbit with a main sequence star surrounded by a field of asteroids. The activity window corresponds to the crossing of that field. (from Smallwood et al. 2019).

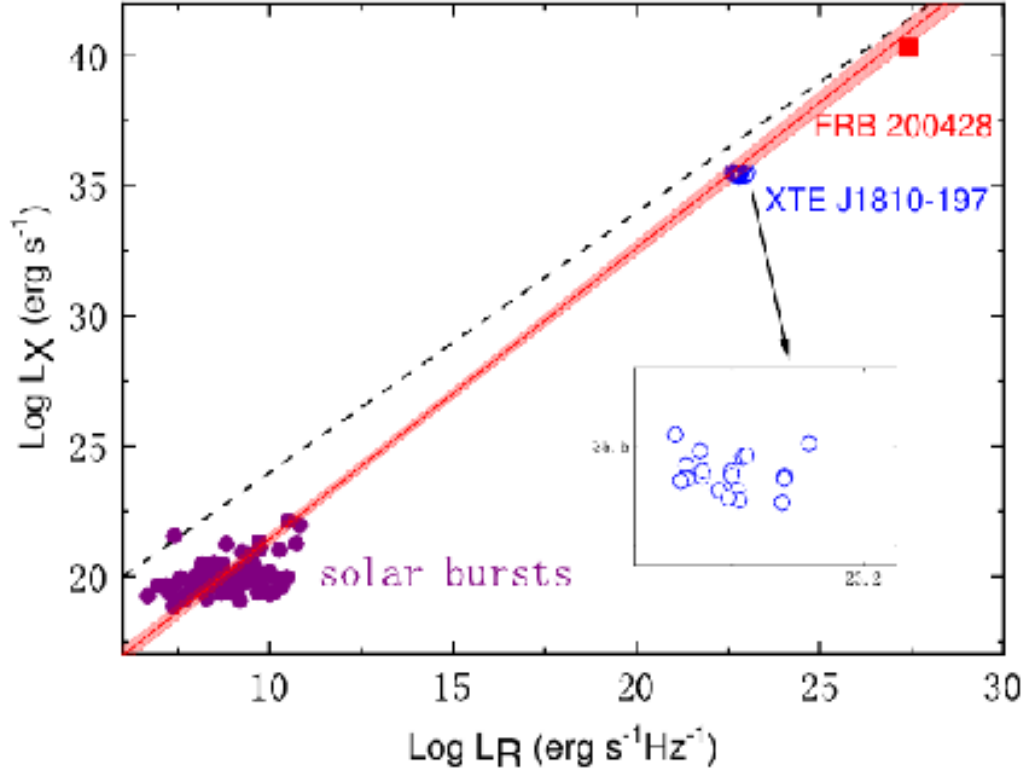
very quickly (compared to the orbital period) the inner magnetospheric region of the NS, and it is unclear what may cause it to spiral so fast.

### 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, one appeals 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). In fact it has been argued that two distinct populations of magnetars must exist, since if all magnetars were born (extragalactic) FRB capable, and lost their energy to form the regular population, then 3 or 4 orders of magnitude fewer magnetars should populate the galaxy (most likely we would not know any) based on the abundance of young magnetars we can derive from FRBs Lu et al. (2020); Margalit et al. (2020). Therefore, these authors suggest that a rare, particularly powerful sub-population of magnetars is responsible for extra-galactic FRBs.

Interestingly, the theory of the 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. 4). 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. 4.** Relation X-ray vs radio isotropic 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 Gdel-Benz correlation, which can only be used the gyrosynchrotron radio emissions, and does correspond to the data. (from Wang et al. 2021).

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, one needs to appeal to very young objects (decades to centuries old).

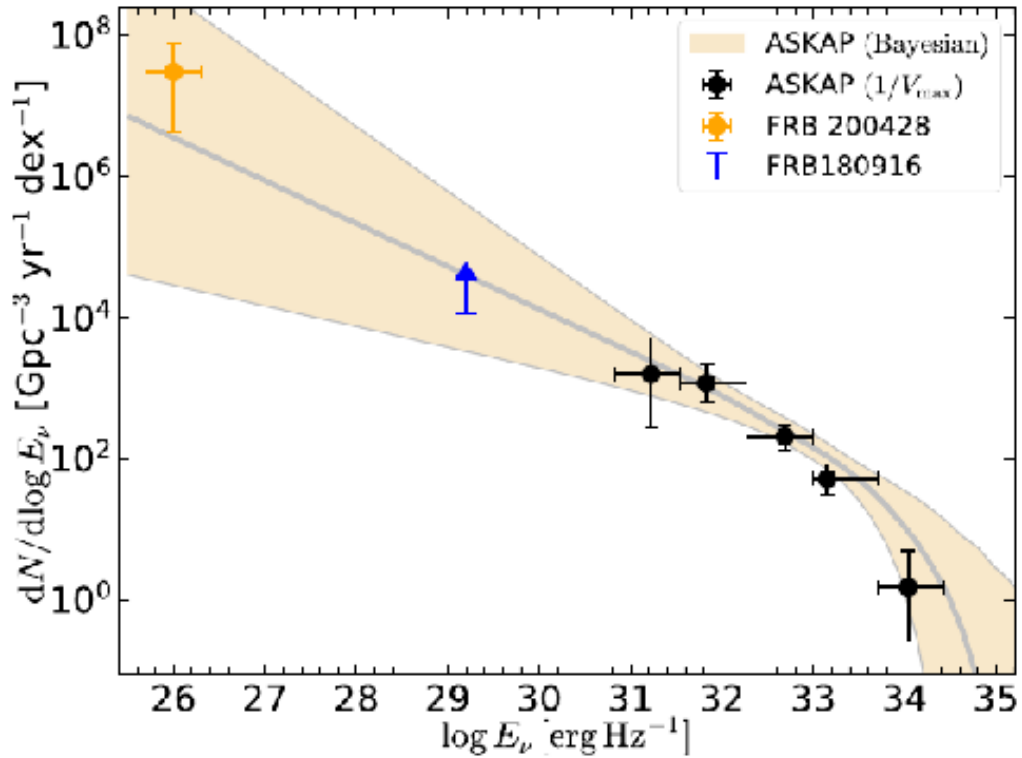
In this case, magnetar activity is expected to decrease very rapidly and measurably over a few years/decades. Another observational consequence is the presence of a nearby dense supernova remnant possibly producing measurable DM and RM variations. This is particularly the case for the loud FRB121102 where both are observed. However, it does not seem to be a generality, as for example the repeater FRB180916 does not show such variations.

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. This in turn creates a large perturbation of the magnetosphere, eventually propagating into the wind zone<sup>†</sup>. This is in few words the commonly admitted model for X-ray bursts from magnetars (Thompson & Duncan 1996). The models presented below differ by the locus of the radio emission, either in the magnetosphere or in the wind, by the emission mechanism itself, and by the way the energy powering the radio emission is conveyed to the emission locus.

<sup>†</sup>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.

### 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. 5). 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.



**Fig. 5.** Volumetric rate of FRB events as a function of their specific energy  $E_\nu$  (intrinsic energy released at frequency  $\nu$ ) 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  $\sim 600$ MHz 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).

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 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; ?).

This sweep may also explain occasional polarisation swings if polarisation depends on the local magnetic field. This is particularly the case for curvature radiation, which also presents the advantage of being mostly linearly polarised, as per the observations.

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 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. It is argued that, because young magnetars have large charge density in their magnetosphere due to the large currents that sustain the twisting of magnetar magnetospheres (Thompson & Duncan 1996), any accelerating electric field is efficiently quenched along closed field lines, quenching at the same the emission mechanism. On the other hand, old magnetars that have dissipated their internal toroidal magnetic field (responsible for the twisting), can undergo charge starvation in a large part of the magnetosphere when it is shaken by a starquake.

### 3.2 Blast wave models

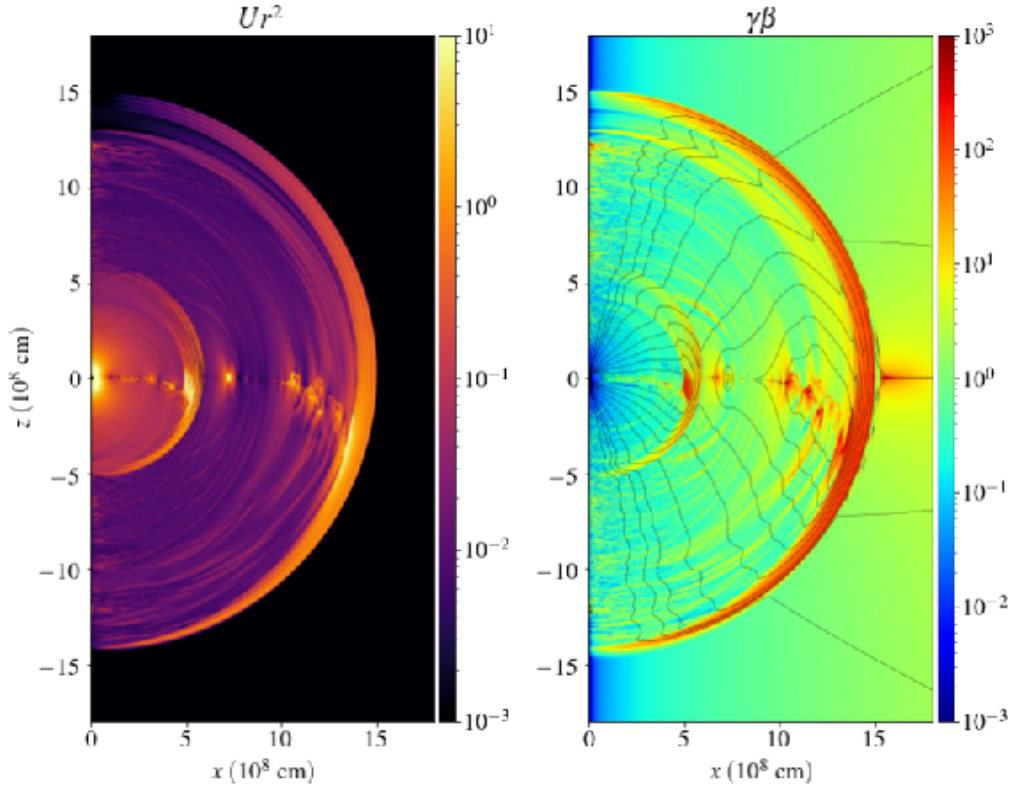
This model is derived from models for short gamma ray bursts (e.g. Lyubarsky 2014; Beloborodov 2017, 2020; Zhang 2020). It considers that, when a starquake occurs, its energy is conveyed through the magnetosphere by Alfvén waves, which eventually provoke magnetic reconnection near the light cylinder. 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 supermagnetosonic 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 (see Fig. 6) 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

#### 3.3.1 Precession(s)

One of the main mechanisms to explain the observed periodicities (16 and 160 days) is the free precession of the star due its quadrupolar moment of inertia (Levin et al. 2020; Zanazzi & Lai 2020). In principle, stress induced by the very strong magnetic field of the star is sufficient to create such a deformation which in turn leads to the precession of the spin axis of the star, very much like a top. Such precession has been long sought in galactic



**Fig. 6.** Force free electrodynamics simulation of plasmoid ejections by Alfvén waves following a magnetar star quake (from Yuan et al. 2020). Left: electromagnetic energy density  $U$  relative to a simple  $1/r^2$  radial dependence,  $Ur^2$ . Right: Lorentz factor  $\gamma$  times velocity  $\beta = v/c$ . One see the wide pancake-like ejecta propagating at large Lorentz factor  $\sim 10^3$  in the magnetar wind. The first ejecta is followed by a denser and variable wind that keeps reconnecting. Following ejecta can create a train of shock in this denser medium, corresponding to a several sub-bursts.

magnetars (Melatos 1999; Glampedakis & Jones 2010), and not found. The reason is that superfluidity in the core has been shown to suppress precession (Shaham 1977). However, very young magnetars could reach a core temperature  $T_c > 10^9\text{K}$  that prevents superfluidity to set in, and make precession possible for extra-galactic FRB sources. If that is so, then a rapid decrease of the precession period is expected over a few years Levin et al. (2020); Zanazzi & Lai (2020).

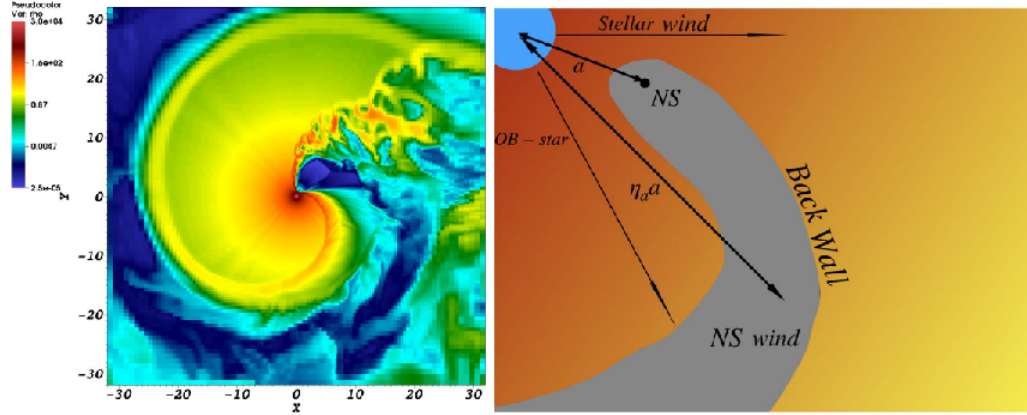
Let us note that precession due to an accretion disk has been proposed as well, with somewhat different properties.

Although this mechanism is independent of whether FRBs are produced inside the magnetosphere or in blast waves in the wind zone, it nonetheless assumes that radio emission is localised within the magnetosphere (and that location is the same at every burst) and somewhat beamed. It can be a problem for blast wave models. The low-twist magnetar model, which assumes an old magnetar, also appears somewhat incompatible because precession is not expected for such stars. However, it has been proposed that very-long period low-twist magnetars could explain the observed periodicities (Beniamini et al. 2020).

### 3.3.2 O/B star companion

In this model, a magnetar is enshrouded in the strong wind of an O/B star companion. The dense plasma absorbs radio emissions from the magnetar by free-free absorption, except in a cavity formed by the tail of the magnetar wind (see Fig. 7). FRBs are produced by the magnetar, but reaches the observer only during the interval of orbital phase where the optical depth is sufficiently small to let the signal out. Periodicity thus results from the orbital motion, and the size of activity window results from the ratio between the two wind powers : the larger the magnetar wind, the larger the cavity, the wider the window. O/B stars thus correspond to the main sequence type with the appropriate range of wind power. In the case of the repeater FRB180916,

the wind of the magnetar must be only mildly strong,  $\sim 10^{37}$  erg/s, in order to account for the 5 days activity window. This excludes very fast spinning magnetars (although being stronger than Galactic magnetars).



**Fig. 7.** 'Left panel: reprocessed simulations of (Bosch-Ramon et al. 2015) of interacting winds of the B star and pulsar. Right panel: artistic image of the interacting winds. The pulsar wind creates a narrow low-density cavity that extends to distances much larger than the orbital separation by a factor  $\eta \sim 1030$ .'(quoted from Lyutikov et al. 2020) At this distance, the B star wind is sufficiently thin and free-free absorption does not prevent radiation from exiting to the observer.

One of the predictions of this model is that the size of the activity window should be frequency dependent, the higher the frequency the broader the window. Small dispersion measure variations are expected due to the turbulent interface between the two winds which continuously changes the gas distribution along the line of sight. Large rotation measure is also expected, and has been seen from the loud FRB121102, but not from the repeater FRB180916. In addition, (Lyutikov et al. 2020) predict that no period shorter than 10 days is expected.

We see that this model makes no assumption as to the emission mechanism from the magnetar and the presence of an O/B companion is a pure matter of circumstances, but not a necessity. It follows that non-periodic repeaters should also be observed. This is a difference with the precession free precession model, where in principle all repeaters should have some periodicity, assuming the source is always the same type of object. We also note that the authors of Lyutikov et al. (2020) argue in favour of a magnetospheric locus of FRB emissions, since by suppressing the magnetar's wind, the close companion also suppresses of the emission loci of blast wave models.

#### 4 Conclusion

A number of reviews on FRBs are available in the literature. Let us mention the 'living theory catalog for fast radio bursts' (Platts et al. 2019)<sup>‡</sup> 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).

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