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# MODELS OF FAST RADIO BURSTS AT COSMOLOGICAL DISTANCES

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**Abstract.** Fast radio bursts are isolated radio pulses of high amplitude, with a frequency / time delay relation that can be interpreted as the dispersion measure (DM) of a source at cosmological distances (several hundreds of Mpc). Up to 2015, the only known FRBs all had different locations on the sky, and different DM. Many theoretical explanations of FRBs have been proposed. Some of them are associated to unique cataclysmic events, others are compatible with the repetition of bursts from the same source. The recent publication of the repeating FRB 121102 shows that at least some of the FRB must be compatible with non-cataclysmic events. A model based on the interaction of a highly relativitic pulsar wind with a body orbiting the pulsar (planet, big asteroid, white dwarf) could explain FRBs. It is briefly compared with other models of repeating FRBs.

Keywords: fast radio bursts, pulsars, wind, cyclotron maser

## 1 Introduction

Fast radio bursts are isolated radio pulses ($\sim$ GHz) similar to a pulsar pulse but of high amplitude (several Janskys). Their duration is typically $\sim$ 5 ms at a given frequency. About 30 FRBs have been observed at the Parkes, Arecibo and Greenbank radio-telescopes since the first discovery in 2006. Their distribution in the sky is not uniform, but not enhanced in the galactic plane (Petroff et al. 2016).

Like pulsar signals, FRBs have a dispersion measure (DM). The DM is a number relating a time delay from the source (at distance $d$) to observer that depends on the frequency,

$$(\frac{t}{s}) = 4.2 \times 10^3 (\frac{\nu}{MHz})^{-2} DM, \quad \text{and} \quad DM = \int_0^d n_e dz, \tag{1.1}$$

where $n_e$ is the electron number density, and the integral is computed along the line of sight. A large DM implies a lot of electrons encountered. The DM of FRBs (>300 pc.cm$^{-3}$) is much larger than those of pulsars (typically less than 150 pc.cm$^{-3}$, even for the most distant ones). There can be two explanations to a large DM : (1) the distance $d$ is large. The source is outside our galaxy, and only "normal" ISM and inter galactic medium (IGM) is met. Or (2) electron density $n_e$ is unusually high somewhere between the source and us. The source can be inside the Galaxy, but there is a somehow dense nebulae/corona... between the source and us. With FRBs, the first hypothesis leads to distances $d \sim 100 - 1000$ Mpc (Lorimer et al. 2007). Let us notice that a few FRBs exhibit scattering; this is characteristic of turbulence in interstellar an/or intergalactic medium (Katz 2016b).

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## 2 Constraining the models of FRBs

What make FRBs so mysterious is their high dispersion measure. Nevertheless, the models of FRB should also explain their brevity, their production rate (extrapolated to $10^3$ to $10^4$ per sky per day), their location in galactic coordinates, and their lack of counterpart (up to now) at other frequencies.

A few special FRBs that could help to validate/invalidate models. For instance, FRB 140514 has 21% circular polarization (Petroff et al. 2015), and FRB 121102 is a repeating one ! Spitler et al. (2016); Scholz et al. (2016).

The repeating FRB 121102 is especially interesting because it is compatible with none of the (many) models based on cataclysmic events. For a total of 60 hours of observation between 2012 and 2016, 17 bursts of FRB 121102 have been observed with Arecibo at 1.4 GHz, 1 in Parkes, 5 with GBT at 2 GHz. None were seen in Lovell, Jansky VLA, and Effelsberg.

The distribution of the bursts is not "regular" : 6 bursts were seen during a 10-min period, and 4 in a 20-min period. All these bursts have the same DM=599 pc $cm^{-3}$ (but two), and the same $\delta$ and RA. The bursts have varied amplitudes, varied spectral shapes that do not exhibit power law Spitler et al. (2016). Bursts number 8 and 10 are double peaked. The bursts of FRB 121102 have no circular nor linear polarization. No periodicity was found. No hard X /soft $\gamma$-ray burst counterpart was found with Swift, Fermi, MAXI, and INTEGRAL.

## 3 Models versus locations of FRB

The models of FRB are numerous, and they correspond to sources at various distances. For instance, models invoking giant flares from a star or compact binary stars suppose a thick plasma layer near the source in order to cause the DM (Loeb et al. 2014). The weak point with this models is the distribution of FRBs in the sky : the galactic disk is not a privileged direction.

The same requirement of DM near the source is associated with models of FRB in nearby galaxies : flares from a magnetar near a galactic nucleus (Pen & Connor 2015), or the interaction of a young pulsar with its supernova remanent (Connor et al. 2016).

For sources in $z \sim 0.2 - 1$ galaxies, the DM excess can come from the inter galactic medium (IGM). Many of these models are based on unique cataclysmic events: NS star collapse into BH, NS merger, but they are not compatible with the repeating FRB 121102.

A popular model since the discovery of the repeating FRB is based on super-giant flare from magnetar Katz (2016a). It explains the DM, the possibility of repeating bursts. But magnetar giant flares are usually bright in X-rays or gamma-rays, and it is not very clear yet why the ones that cause FRB would only be seen in radio waves (Tendulkar et al. 2016).

Another very popular model considers a super-giant-Crab-like pulse (Katz 2014). It is compatible with the random succession of bursts, and the excess of DM can be caused partly in the vicinity of the source, and partly in the IGM. The idea of super-giant-Crab-like pulses is particularly interesting because the Crab giant pulses are random radio signals without couterpart at other wavelengths, as is the case with FRBs.

Actually, this model, and the model of super-giant flare from magnetar, are based on extrapolation of the properties of well known signals, but not yet on a well founded theoretical explanation. For instance, there are explanations to the giant pulses of the Crab, but not to the 1000 times more energetic pulses that would correspond to the FRB. It seems that some more theoretical work must be done.

Other models of very distant sources of FRB invoke bodies orbiting or falling on pulsars. Geng & Huang (2015); Dai et al. (2016) have developped a model of FRB caused by asteroids falling on a neutron star. This model is partly inspired from an old (and finaly discarded) model of gamma-ray burst developped by Colgate & Petschek (1981). It can explain the release of energy, possibly in the form of radio waves.

Mottez & Zarka (2014) have developed a model that invoke planets, large asteroids, or white dwarfs, orbiting a pulsar in interaction with the pulsar wind. This model is compatible with sources at cosmological distances, despite the relatively low amount of energy that they require (see section 4).

The models of magnetar super-giant flares, of Crab-like-super-giant pulses, or asteroid fallback, and pulsar orbiting bodies are all compatible with a repeating source of FRB at cosmological distance, or a least in another galaxy.

We outline now the main concepts associated to the Mottez & Zarka (2014) model.

## 4 Pulsar companions and the extreme collimation of radiation when the radio-source comes at relativistic speed

When a source of radiation propagates at relativistic speed, the radiation is focused in the direction of the motion of the source, along a cone that, for high Lorentz factors has a characteristic angle $\sim 1/\gamma$. This means that (1) the signal is perceptible from a narrower range of angles, (2) all the energy is focussed a narrow solid angle $\sim 1/\gamma^2$, therefore it corresponds to a strong amplification of the received signal, in comparison to what would be obsered in the reference frame of the source.

Active nuclei galaxies provide a well-known example of relativistic aberration. Many active galactic nuclei are associated with a relativistic jet with a Lorentz factor about $\gamma \sim 10$. When we, observers, are along the axis of the jet, we observe very bright emissions, called BL Lac, and this brightness is caused by the relativitic aberration.

Pulsars are surrounded by winds of electron and positron plasmas (possibly also with ions) with Lorentz factors that could reach values up to $10^6$ or more... Let us suppose that this wind is perturbed by a solid body orbiting into it. If the perturbation is directly attached to the planet, the source moves with the planet, and is not relativistic, and nothing is expected to be observed over long distances. But the planet can develop a structure that extends far from the solid planet into the wind. If the planet is magnetized, and if the wind is super-Alfvénic, this can take the form of a magnetosphere. But we know that the pulsar wind, as long as the magnetic energy is not dissipated, is sub-Alfvénic (Mottez & Heyvaerts 2011b). (Both the Alfvén velocity $v_A$ and the plasma speed $v_W$ are close to $c$ but $v_W < v_A$.)

In that case, two stationnary Alfvén waves anchored to the planet are long structures that extend very far from the solid planet into the wind. They are called Alfvén wings*. Their angle with the wind direction is very small (Mottez & Heyvaerts 2011b,a).

Therefore when the pulsar wind crosses this structure, it is perturbed by it during a short fraction of a second (in the observer/planet frame). Then, it is the source of radio emission triggered by a cyclotron maser instability. Therefore, the source composed of this perturbed pulsar wind propagates at the highly relativistic velocity of the pulsar wind. This represents an extreme case of relativistic aberration, where a signal of moderate amplitude (compared to a cataclysmic event, or a flare) that is emitted continuously, can give rise to a FRB like radio-signal that is observables hundreds of Mpc away, during the few milliseconds during which the neutron star, the planet (more precisely, the associated Alfvén wing) and the observer on Earth are aligned Mottez & Zarka (2014, 2015).

## 5 Models invoking asteroids are plausible because small bodies can survive near a neutron star

Two of the above cited models consider that small bodies can approach a pulsar, and possibly fall onto it. Considering the amount of energy radiated by a pulsar, it may seem strange that they are not quickly evaporated at low distances. Actually, most of the energy is released in the form of a pulsar wave (Deutsch 1955). This is a strong magnetic wave radiating at the pulsar rotation period $P_*$ in the range $10^{-3} - 10$ s. This is a high rotation frequency, but a very low electromagnetic wave frequency corresponding to wavelengths much larger than the size of a small pulsar companion. This makes absorption of wave energy very inefficient. Following the Mie theory, the absorption rate of energy of a $\sim 1$ km asteroid is smaller than those of a large companion by about six orders of magnitude. Then, asteroids can survive hundred of thousand years at close distance from a pulsar, when larger bodies cannot (Kotera et al. 2016).

## 6 The pulsar companion model of FRB: compatibility with recent observations

According to this model, a single body orbiting a pulsar would be the cause of a signal (a few ms long) that is repeated periodically, at every revolution of the body (a few hours to a few months or years). Up to now, no periodic FRB repeater has been observed. But we have no proof that the known FRBs are non periodic, because none of them has been observed continuously over periods covering days... or months.

The repeating FRB 121102 could be caused, not by a single body orbiting a pulsar, but with a stream of large asteroids that could, for instance be the result of the tidal disruption of a planet. We have said that 6 burst were seen during a 10-min period, and 4 in a 20-min period. This is compatible with the fact that some of

*Alfvén wings exist with non-magnetized as well as with magnetized bodies.

these asteroids could remain gravitationally bound, like the many asteroids seen in the solar system that evolve in groups of two or three (126 groups of two in the asteroid belt, 7 groups of three).

The model also shows that bursts would be typically composed of four or two peaks would be emitted. More if the body cross the line of sight in a time longer than the pulsar period. The bursts intensities depend on the size of the body, on its distance to the neutron star and on the Lorentz factor of the wind. The two brightest peaks can have the same amplitude, or very different ones. This is compatible with pulses with a single peak (the majority of the observed pulses), if the two bursts are not resolved in time, or if only one peak amplitude is above the detector noise level. The model of Mottez & Zarka (2014) is also compatible with the two double peaked bursts observed with FRB 121102.

## 7 The pulsar companion model of FRB: compatibility with other models

The model of FRB caused by bodies orbiting pulsar have a common point with those of FRB caused by asteroids falling onto the neutron star : they both involve a neutron star and objects orbiting it. But there are many differences. The Mottez & Zarka (2014) model is like those of a light-house, with a continuously emitted radiation that we capture only when the observer is in the (extremly narrow) emission-beam. The Geng & Huang (2015) model suppose that the time during which the radio-waves are emitted corresponds to the destruction of the asteroid near the star surface, and there is no relativistic aberration induced beam focusing.

The Mottez & Zarka (2014) model has nothing either in common with the popular model of magnetar super-flares. The flares are supposed to be caused by restructurations that are internal to the neutron star.

Conversely, the Mottez & Zarka (2014) model could be compatible with those of the super-giant-Crab-like pulses. Indeed, if we consider the young Crab pulsar as a neutron star surrounded by a high amount of small-size asteroids (condensed debris from the supernova), each of these asteroids in the Crab wind could be associated with Alfvén wings. Consequently, each of those asteroids would be a radio source that would behave like a mini-FRB.

Actually, the Geng & Huang (2015) model would be also compatible with a model of Crab giant pulses, if each pulse is caused by an asteroid falling onto the Crab neutron star. But the Mottez & Zarka (2014) would have the advantage of explaining why the Crab giant pulses are only seen in radio, when counterparts at other wavelengths could be expected from asteroids falling onto the star[†].

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