Tidal Disruption of Magnetars as the Sources of Fast Radio Burst

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Abstract

Fast Radio Bursts (FRBs) are mysterious millisecond duration radio transients, and some FRBs repeat. FRBs are highly polarized, indicating that the source is within a strong magnetic field. I hypothesize their origin as Tidal Disruption Events (TDEs) of magnetars by black holes. The TDE releases energy stored in the magnetic field of the magnetar, producing an FRB. Occasionally the magnetar is disrupted into multiple debris chunks, and as individual chunks get consumed, multiple FRBs are produced, forming a repeating FRB. Another process of formation of repeating FRBs is starquakes on magnetars because of tidal forces from black holes. Due to the strong magnetic field of the accretion disk, the FRB is produced in jets. Sometimes the magnetar debris surrounding the magnetic field gets accelerated, producing Ultra-high energy cosmic rays, whose source remains unknown. The FRB signal produced gets polarized by the magnetosphere of the accretion disk and intergalactic magnetic fields.

1   Introduction

Fast radio bursts (FRBs) are radio frequency transient astronomical events with a duration ranging from a fraction of a millisecond to a few milliseconds. Some FRBs are found to repeat, like FRB 121102 and others. Around 40 FRBs are detected to date, and their origin remains unknown. FRB signals are polarized, which suggests that the source is within a strong magnetic field, which I take as a clue of its origin. FRBs have very high dispersion (DM) such as 375 pc cm-3 ([12]) for the Lorimer burst, much greater than that of the Milky Way $DM_M = 45$ pc cm^{-3}([11]), indicating that they have an extragalactic origin. Measurements of various DM of FRBs can be found at the catalogue FRBCAT [1] ([15]). The Dispersion Measure DM of a FRB signal can be approximated by the following equation ([9]):

$$DM = \int_0^d n_{\text{e}} dl \tag{1}$$

in (1) d is the distance traveled by the FRB signal and n_{e} is the number density of electrons along d.

   In this paper, I hypothesise the origin of FRBs as Tidal Disruption Events (TDEs) of magnetars, in which a magnetar is tidally disrupted by a Black hole. My hypothesis

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[1]http://frbcat.org/

is for explaining the origin of a sub-population of FRBs (including repeating FRBs), if not whole population of FRBs. Magnetars are stellar remnants formed by supernovae of massive stars. Magnetars are highly magnetic Neutron stars, with magnetic fields reaching strengths of 10^9 to 10^{11} T (Tesla) and energy density $4.0 \times 10^{25} Jm^{-25}$ ([1]). These strong magnetic fields contribute to the magnetosphere of the FRB disk, giving rise to highly polarised signals as observed. A magnetar TDE can occur either by a black hole encounter or by external disturbance(such as a close flyby of a star) leading the magnetar into the black hole. Such magnetar-black hole pairs can form in many ways:

a)Supernova of a star around a black hole leading to a magnetar

b) Magnetar capture by Black hole

c)A binary system consists of two massive stars. When they die in a supernova explosion, one star leaves behind a black hole while the other leaves behind a magnetar.

A Magnetar- Black hole pair has already been discovered ([10]). A magnetar SGR 1745-2900 has been found around Sagittarius A* (Sgr A*). Later on into the TDE, the magnetar debris falls back to form an accretion disk. The strong magnetic field of the accretion disk coupled with the magnetic field from the black hole via Blandford-Znajek gives rise to strong, collimating magnetic fields which concentrate the signal into a jet.The reason behind the observation of only a few FRBs can be explained by my hypothesis: as the jet needs to be directly pointed towards us in order to observe, such observations are rare (along with other reasons). Hence the low number of detected FRBs can be explained by my , because the rate of FRBs is predicted to be 10^4 day⁻1 sky⁻1 by [7].

Sometimes, an FRB signal is found to repeat, such as FRB 121102, FRB 180814 and others. They can be explained by my hypothesis, refer 2.1 for more details into the hypothesised process. In some FRBs, the debris from the magnetar gets accelerated by the magnetic field of the disk and also by the jet ([8]). These charged particles may be Ultra-High Energy Cosmic rays according to my hypothesis.

[4] has localised FRB 180916 to a nearby spiral galaxy. They found fast radio burst in a star-forming region. This supports my hypothesis as magnetars are much more common in these places, as many massive stars form and die here in a supernovae, giving rise to magnetar(s) and stellar black hole(s), which in turn give rise to FRBs.

2 Magnetar Tidal Disruption and Fast Radio Burst Model

2.1 FRB Model Overview

My model of FRBs explains their origin as tidal disruption of a magnetar by a black hole. My model explains the origin of a sub-population of FRBs, if not all FRBs. This process takes place in multiple steps: from pericenter passage of the magnetar to jet formation and emission. The emission occurs as a result of the loss of the binding energy, orbital energy, and the strong magnetic energy of the magnetar. The emission is produced in Radio wavelengths, with possible afterglow in X-Rays and other bands (see section 2.6 for more information). In some cases the magnetar forms 'chunks' of debris, which happens when the self gravity (in small scales within the debris streams) overcomes the tidal forces, and as each chunks get consumed by the black hole multiple FRBs are produced. The constant recurrence of repeating FRBs is caused by the tidal stream initially breaking apart into multiple streams (as depicted in 1), and then the debris in those streams coalesce to form debris chunks. Hence chunks formed from different parent streams will get consumed after regular intervals based on their orbits and distance from the black hole. This whole process can happen when the magnetar just grazes past the tidal sphere, where the tidal forces are comparatively weaker, with

respect to TDEs occurring much deeper within the tidal sphere. Another possible way of repeating FRBs to occur based on my hypothesis is fracturing of magnetar' s crust (unlike [18], in my idea the fracturing is due to tidal forces from the black hole) over time due to tidal forces from the black hole, releasing huge amounts of radio energy stored in the magnetar' s crust and giving rise to repeating FRBs. Observed properties of FRBs can be also be explained by my hypothesis. The burst duration is discussed below in section 2.2. Polarization of emitted electromagnetic (EM) radiation arises from my hypothesis as a result of propagation through the strong magnetic field of the magnetar.

My hypothesis is further supported by a discovery that magnetars are most likely the source of Fast Radio Bursts (The Astronomer's Telegram [2]). This also proves my hypothesis observationally.The observed high dispersion measure also arises from my hypothesis. A part of dispersion measure DM_m is based on the electron column density around the magnetar (1). Based on (1), we can come to the conclusion that

$$DM \propto n_{\mathrm{e}} \tag{2}$$

Based on [6], as N_{H} is high in ISM and WHIM; and the electron (and positron) column density is high around magnetars ([2]), the DM is high (based on (2) and [6]; [2]). This explains the high DM of FRB observations (visit FRBCAT for data). Soon after the magnetar crosses R_{isco}, the magnetar forms an accretion disk which gives rise to an environment full of electrons and positrons around the black hole, and hence a greater DM as the FRB signal propagates.

2.2   Burst Duration Calculation

The timescale of the FRB burst can be approximated as the orbital period of the final orbits of the magnetar around the black hole. This is because soon after the final orbits, the processes occur in rapid succession, hence the only useful timescale is the orbital period of the final orbits. The timescale of the final orbits can be calculated based on the radius of the Innermost Stable Circular Orbit R_{isco} because it gives the separation between the magnetar and the black hole moments before tidal disruption begins, because soon after the magnetar cross R_{isco}, it disrupts and the phases of TDE begin and happen in rapid succession. R_{isco} is given by:

$$R_{\mathrm{isco}} = \frac{6GM_{\mathrm{BH}}}{c^2} = 3R_{\mathrm{s}} \tag{3}$$

in (3), G is the universal gravitational constant, M_{BH} is the mass of the black hole, c is the speed of light, and R_s is the schwarzschild radius. The separation d (based on R_{isco} as discussed above) will hence be equal to $R = 6 \times R_{\mathrm{s}}$. Solving (3) based on Kepler's laws for orbital period gives:

$$t = \sqrt{\frac{R^3}{GM_{\mathrm{BH}}}} \tag{4}$$

When (4) is solved for a 10 $\mathrm{M}_\odot$ Stellar Mass Black Hole the duration of the FRB burst is found to be 2.04 ms, which matches with various FRB observations. Stellar Mass Black Holes were chosen for the calculation as they are relatively common and are found many in binary systems. When (4) is solved over the range of masses of observed candidates of Stellar Mass Black Holes ($\sim 4M_\odot$ to $\sim 68M_\odot$), the results are found to be in the range of 0.5 ms to 36 ms. This range completely matches with observations (visit FRBCAT for data of FRBs). In fact, both the ranges of calculated pulse duration and observed pulse duration overlap, and many FRBs are found to lie within the range of the obtained result. Hence, my hypothesis also explains the duration of FRBs.
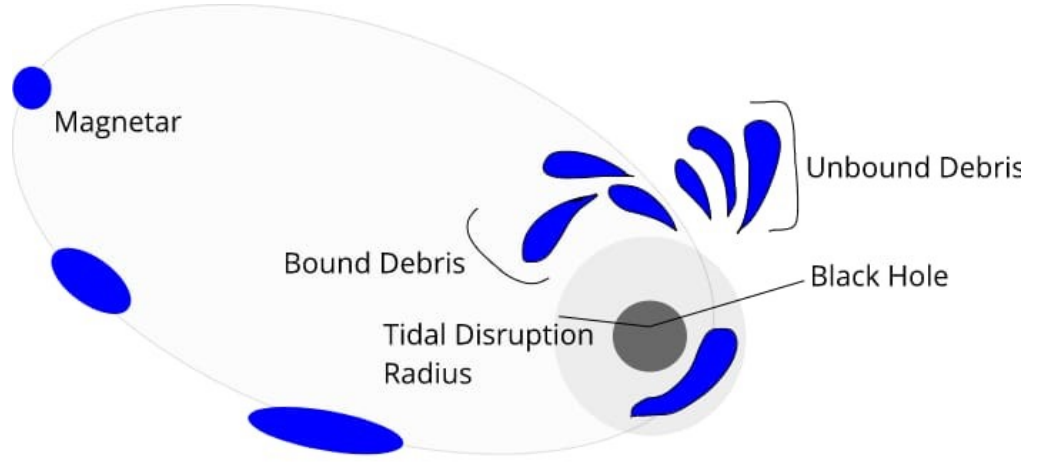
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[2]http://www.astronomerstelegram.org/?read=13681

Figure 1. Pericenter passage of the magnetar. Around half of the debris is unbounded and it escapes, while bounded debris returns back to the black hole. The debris is in the form of streams, as discussed in 2.4. The bounded debris falls back to give rise to an accretion disk, which in turn gives rise to an FRB.

2.3 Pericenter passage and Black Hole encounter

The tidal disruption process begins with scattering of the magnetar into the loss cone of the black hole ([5]). This may occur as a result of another body influencing the orbit; or by emission of gravitational waves. Once inside, the magnetar heads towards the black hole. The tidal disruption occurs only if the pericenter distance R_p is less than the tidal disruption radius R_t. R_t can be represented mathematically as:

$$R_{\mathrm{t}} \approx R_{\mathrm{m}}\Big(\frac{M_{\mathrm{BH}}}{M_{\mathrm{m}}}\Big)^{\frac{1}{3}} \tag{5}$$

In (5), R_{m} denotes the radius of the magnetar, M_{BH} denotes the mass of the black hole, and M_{m} denotes the mass of the magnetar. The depth of the TDE within the Tidal sphere is given by the penetration factor β:

$$\beta \equiv \frac{R_{\mathrm{t}}}{R_{\mathrm{p}}} \tag{6}$$

The tidal disruption radius marks the boundary beyond which the tidal forces F_t from the black hole exceed the self-gravitation forces F_s. Hence, tidal disruption events can occur only if $R_{\mathrm{p}} < R_{\mathrm{t}}$, which from (6) can be represented as $\beta > 1$ for a TDE to occur. In order to detect the FRB from TDE of the magnetar, the magnetar TDE must take place outside the event horizon of the black hole. The radius of the event horizon,i.e the Schwarzchild radius R_s, can be calculated by the following equation:

$$R_{\mathrm{s}} = \frac{2GM_{\mathrm{BH}}}{c^2} \tag{7}$$

in (7) c is the speed of light in a vacuum , G is the Universal Gravitational Constant and M_{BH} is the mass of the black hole. Therefore R_{t} ¿ R_{s} in order for the magnetar TDE to be detectable. The strength of the tidal disruption η by [17] is a dimensionless parameter given by:

$$\eta = \Big(\frac{M_{\mathrm{m}}}{M_{\mathrm{BH}}}\frac{R_{\mathrm{p}}^{\,3}}{R_{\mathrm{m}}}\Big)^{\frac{1}{2}} \tag{8}$$
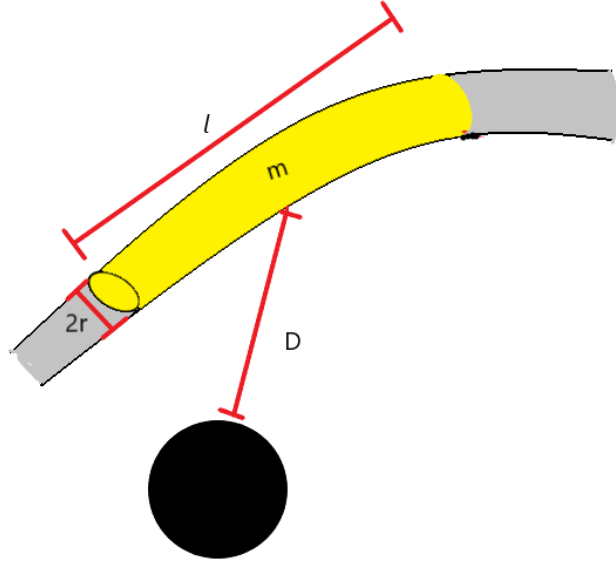
Figure 2. A typical stream formed from tidal disruption of a magnetar. m is the mass of the stream, l is the length of the stream, r is the radius of the stream element and D is the distance between the magnetar stream and the black hole.

Whenever $\eta \leqslant 1$, the magnetar will be disrupted in a single flyby ([17]). During pericenter passage, the magnetar deforms(1) under tidal influence from the black hole. As per [5] the deformation leads to a spread in orbital energy $\Delta\epsilon$:

$$\Delta\epsilon = \frac{GM_{\mathrm{BH}}}{R_{\mathrm{t}}^{2}} \qquad (9)$$

2.4   Stream Evolution

This is the next phase of the tidal disruption event of the magnetar. After pericenter passage and tidal deformation, the tidal forces disrupt the magnetar into long stream-like structures (2). The stream has a linear density λ (by [5]):

$$\lambda \approx \frac{m}{l}. \qquad (10)$$

where l in (10) is the length and m is the mass of the stream element. The volume V of the stream can be approximately calculated by using the method of solids of revolution by disks(with area A), by integrating the area of the disks over the length l of the magnetar stream.

$$A = \pi r^{2} \qquad (11)$$

because the radius r is not constant throughout the magnetar stream, I considered it as the value of the function $f(l)$ at any point along l. Hence $r = f(l)$. Now (11) can be represented as:

$$A = \pi f(l)^{2} \qquad (12)$$

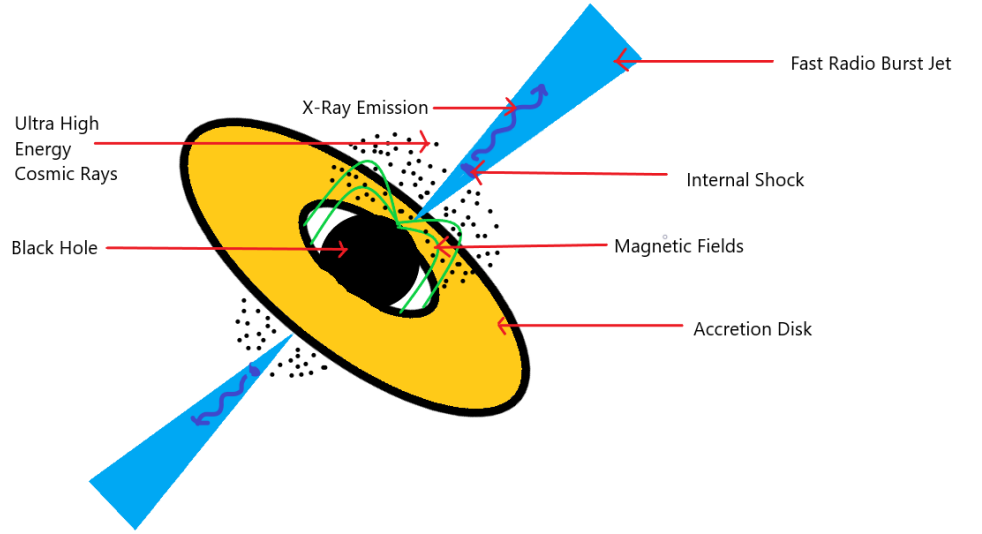Now by integrating (12) over the range $0 \rightarrow l$:

Figure 3. As the stream falls back, it forms an accretion disk and a FRB. The magnetic fields then polarize the FRB. Sometimes the particles around the Jet or the FRB magnetosphere can get accelerated, giving rise to Ultra High Energy Cosmic , represented by red dots in this figure.

$$V = \int_0^l \pi f(l)^2 dx = \pi \int_0^l f(l)^2 dx \tag{13}$$

By solving (13), I obtained:

$$V = \frac{\pi f(l)^3}{3} \tag{14}$$

Then the density of the stream ρ according to (14) is:

$$\rho = \frac{m}{V} \rightarrow \rho = \frac{3m}{\pi f(l)^3} \tag{15}$$

by simplifying (15) and substituting λ from (10):

$$\rho = 0.95 \Big(\frac{\lambda}{f(l)^2} \Big) \tag{16}$$

Or by simply assuming that the stream is in the form of a cylinder,

$$\rho = \frac{m}{\pi r^2 l} \tag{17}$$

Sometimes the stream may form magnetar debris chunks due to self gravitation being greater than the tidal forces, which may happen when the TDE doesn't deep within the Tidal Disruption Sphere. Whenever these debris chunks get consumed by the black hole. In some scenarios the tidal forces on the magnetar may cause starquakes, which can also give rise to repeating FRBs.

2.5   Disk and FRB Jet formation

After the phase of stream evolution, bound magnetar debris stream falls back onto the black hole, giving rise to an accretion disk and a FRB jet. The mass fallback rate is

given by :

$$\dot{M} = \frac{dM}{dt} \tag{18}$$

[5] has applied chain rule to (18). The result is as follows:

$$\dot{M} = \frac{dM}{d\epsilon}\frac{d\epsilon}{dt} = \frac{(2\pi M_{\mathrm{BH}})^{\frac{2}{3}}}{3}\frac{dM}{d\epsilon}t^{-\frac{5}{3}} \tag{19}$$

After fallback the debris forms an accretion disk. The accretion disk then feeds the black hole, which gives rise to an FRB. Using the Thin Disk Approximation that height H of the disk relates with radius of the disk R as $H << R$ and the disk is axisymmetric, and also the mass of the disk is negligible compared to the black hole. Hence the angular velocity $\Omega(R)$ will be in Keplerian Form:

$$\Omega(R) = \Big(\frac{GM}{R^3}\Big)^{\frac{1}{2}} \tag{20}$$

As a result of combination of loss of orbital energy, magnetar binding energy, and magnetar magnetic field decay , a short burst (due to compactness of magnetar material) in order of milliseconds (4) in radio wavelengths is produced, along with some multiwavelength emissions, which is observed as a Fast Radio Burst on Earth.

The accretion disk has very strong magnetic field, as a result being composed of magnetar material. This magnetic field contributes to the existing magnetic field caused by Blandford-Znajek process ([3]), giving rise to very strong, collimating magnetic fields. These magnetic fields then collimate the FRB signal, giving rise to a FRB jet. As this jet travels, it passes through higher regions of the strong magnetosphere of the disk. These magnetic fields polarize the FRB jet. The polarization is observed to be 21±7 percent circular polarized averaged over the complete FRB by [14]. The amount of induced rotation RM in FRB signal is ([14]):

$$RM \propto \int\limits_0^d n_{\mathrm{e}}B_{\parallel}dl \tag{21}$$

where n_{e} is electron column density and $B_{\parallel}$ is magnetic field parallel to the line of sight. (21) can be simplified to $RM \propto n_{\mathrm{e}}$, $RM \propto B_{\parallel}$. Both of these values are very high in magnetar TDEs, hence the observed rotation measure is high. Finally, as the FRB signal travels, it passes through Warm Hot Intergalactic Medium (WHIM). The intergalactic magnetic fields also contribute to the polarization of the FRB signal.

Sometimes, as discussed in section 2.4, some parts of the stream clump together to form relatively small 'chunks' of debris. The reason behind this is self-gravitation overcoming the tidal forces from the black hole, which may happen when the pericenter distance is relatively far, but within the tidal disruption radius. As each of these chunks get consumed by the black hole, a huge burst of energy is released, which is observed as a repeating FRB. In some scenarios, the debris collides with Interstellar Material, which causes the debris to decelerate and give rise to shocks. These shocks might accelerate electrons to relativistic velocities, giving rise to non-thermal, synchrotron radiation ([13]). This further strengthens the radio emission from the FRB.In a few scenarios, during the first phases of TDE the magnetar's crust is subject to enormous stresses from tidal forces from the black hole. This results in breaking of the crust, which releases the huge amount of energy stored in the magnetic fields embedded in the crust, giving rise to a starquake. As multiple starquakes occur, multiple bursts are produced, which is observed as a repeating FRB.

2.6 Multiwavelength and Follow Up Observations

[14]'s real-time follow-up observations of FRB 140514 revealed multiple characteristics of FRBs. [14] used *Swift* (X-ray) and Giant Metrewave Radio Telescope (GMRT). These telescopes identified two X-Ray sources and a radio source respectively within 14.4 arc-minutes of the Parkes Beam, i.e, FRB 140514. [16] also found similar results: they had found an X-Ray source CXOU J053156.7+330807 using Chandra X-Ray Observatory. Based on observations of its Hydrogen column density N_H and the DM of FRB121102, the X-Ray source is likely to be associated with FRB121102, and FRB121102 (A repeating FRB) can be explained by my hypothesis. These X-ray sources can be very easily explained using my idea that FRBs are formed as a result of magnetar tidal disruption, as the jets associated with TDEs are expected to glow in X-rays too ([19]), as a result of internal shocks([19]).

Therefore my hypothesis that magnetar tidal disruption events cause fast radio bursts, can explain the origin of the two X-ray sources: a result of TDE jet internal shocks found near FRB 140514. The radio source found by GMRT can be thought of as radio emissions from the other FRB jet, although this fact also depends on the orientation of the jets with respect to the observer. If the jet points directly towards us we observe only one, bright source. If we observe the jet at an angle, we see 2 sources. The two x-ray sources detected by *Swift* might correspond to those two points created by internal shocks in the FRB jets. In radio wavelengths, whenever a FRB jet is observed at an angle, two radio sources are observed. The jet closely oriented toward us is interpreted as the burst, while the second jet is observed as another radio source. That second radio source might correspond to the radio source detected by GMRT. [14] mentioned that any theory explaining the progenitor of FRBs must explain the polarization associated with them, and my hypothesis readily explains the origin of the polarization; The polarization is due to the magnetic field of the accretion disk and the jet, along with contributions from other sources and processes during the journey of the signal to Earth, such WHIM magnetic fields.

3 Conclusions

Fast Radio Bursts are millisecond duration radio transients of unknown origin. Their signals are strongly polarized. Calculations expect the rate of FRBs to be 10^4 day⁻1 sky⁻1 ([7]), yet very few are observed. Their dispersion measure suggests that they have an extragalactic origin.

In this paper, I hypothesise the origin of FRBs as tidal disruption of magnetars by black holes. The tidal disruption releases the orbital energy, the binding energy of the magnetar, and the and the energy stored in its strong magnetic field in the form of a burst of radio energy from the jets. These jets glow in multiple wavelengths, with the shocks in the jets giving rise to X-Ray emissions. The rareness of FRBs according to my hypothesis is that they are produced in jets, and we can observe FRBs only if one of their jets point towards us (which is rare), hence only a few FRBs are detected. The expected emissions based on my hypothesis match with the observations of FRB 140514 ([14]) as discussed in section 2.6 . The polarization of FRBs, according to my hypothesis, is due to the strong magnetic field of the accretion disk and the black hole along with effects from WHIM magnetic fields.

Therefore my hypothesis explains

- Origin of Fast Radio Bursts

- Polarization of Fast Radio Bursts

- FRBs as the origin of Ultra High Energy Cosmic Rays

- Repeating Fast Radio Bursts ₂₃₈

- The rareness of Fast Radio Burst observations ₂₃₉

A few FRBs have been localised to their sources. FRB 180916 has been localised to a ₂₄₀ star-forming region in a spiral galaxy by [4]. This supports my hypothesis, as magnetars ₂₄₁ and black holes are more common in star-forming regions. ₂₄₂

In conclusion, I hypothesize that Fast Radio Bursts are caused by tidal disruption of ₂₄₃ magnetars by black holes. The energy is released in the form of twin jets. Repeating ₂₄₄ FRBs are caused by black holes swallowing multiple debris chunks and also by ₂₄₅ starquakes on the crust of the magnetar. Sometimes debris particles can get accelerated ₂₄₆ due to the strong magnetic field of the accretion disk, which may give rise to Ultra High ₂₄₇ Energy Cosmic Rays. As the FRB jet propagates, it passes through the upper ₂₄₈ magnetosphere of the disk and Warm Hot Intergalactic Medium, which gives rise to ₂₄₉ polarization. Because an FRB can be observed only when specific alignment (FRB jet ₂₅₀ directly pointed towards us) is present, FRBs are rare. The expected emission, Radio ₂₅₁ and X-Ray (from internal shocks inside the FRB jet ([19])), match with the ₂₅₂ observations ([14]). ₂₅₃

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