Are Fast Radio Bursts Made By Neutron Stars?

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ABSTRACT
Popular models of repeating Fast Radio Bursts (and perhaps of all Fast Radio Bursts) involve neutron stars because of their high rotational or magnetostatic energy densities. These models take one of two forms: giant but rare pulsar-like pulses like those of Rotating RAdio Transients, and outbursts like those of Soft Gamma Repeaters. Here I collate the evidence, recently strengthened, against these models, including the absence of Galactic micro-FRB, and attribute the 16 day periodicity of FRB 180916.J0158+65 to the precession of a jet produced by a massive black hole's accretion disc.

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OUTLINE

- Background & Introduction
- Pulsar-like models of FRB
- SGR-like models of FRB
- FRB sky distribution
- FRB 180916.J0158+65
- Discussion

INTRODUCTION

- A **Fast Radio Burst** (FRB) is a transient radio pulse of length ranging from a fraction of a millisecond to a few milliseconds.
- The first FRB was discovered by **Lorimer et al. in 2007** when they were looking through archival pulsar survey data, and it is therefore commonly referred to as the Lorimer Burst.
- Many FRBs have since been recorded, including several that have been detected to repeat in seemingly irregular ways.
- But, one FRB as of February 2020, has been detected to repeat in a regular way: **FRB 180916** seems to **pulse every 16.35 days.**
- The exact origin and cause of FRB are uncertain and most are thought to be of extragalactic origin.

INTRODUCTION

- The sources and mechanisms of Fast Radio Bursts (FRB) are one of the most prominent mysteries of modern astronomy.
- Most models involve **neutron stars** to take advantage of their deep gravitational potential wells, the great magnetostatic and rotational energies (of some neutron stars) and their other known transient emissions.
- **Pulsar-like models** provide a natural analogy to the coherent emission of FRB.
- Magnetostatic energy (“magnetar”) models of **Soft Gamma Repeaters (SGR)** readily provide the energies of FRB

Although many models of pulsars and magnetars have been developed, none of them led to a prediction of FRB, as might have been expected were FRB their natural consequence. These models require very large extrapolations, quantitative (in energy) or qualitative (in the type of emission) to account for FRB, which suggests re-examination of the assumption that neutron stars are responsible.

INTRODUCTION

- Neutron star models have difficulty explaining repeating FRB because the well-studied **repeating FRB 121102 is not periodic (Zhang et al. 2018)**
- Magnetic fields are essential to pulsar and “magnetar” SGR models of FRB.
- Magnetic fields vary with direction from their source, as will any radiation related to the field.
- Radiation energized by a neutron star’s rotationally swept fields or particles may be emitted far away, perhaps in a wind nebula or supernova remnant.
- Brief bursts, like FRB, emitted by interaction with distant small structures would also be rotationally modulated, although continuous emission need not be.
- These difficulties arise in any neutron star model that involves a magnetic field: pulsar-like, SGR-like and accretional models in which a magnetic field channels accretion.

INTRODUCTION

The arguments presented in this paper are not universally accepted, and neutron star models remain popular.

- It is a strong argument against pulsar-like models, whose rotation implies bursts separated by integer multiples of a rotation period.
- It is a somewhat weaker argument against SGR-like models in which it only implies periodic modulation of the observed strengths and frequencies of bursts.

The purpose of the article is to synthesize arguments against any neutron star origin of FRB.

PULSAR-LIKE MODELS OF FRB

- In these models FRB are produced by the same mechanisms as **radio pulsars**, but with much higher energies and with most pulses nulled.
- Such models imply pulse intervals that are **integer multiples of** a neutron star's **rotation period**.
- This appears to be inconsistent both with older data (Hardy et al. 2017; Scholz et al. 2017) and with a series of 93 bursts observed in one five-hour observing run of the repeater FRB 121102 (Zhang et al. 2018).
- Such a run is short enough that plausible period derivatives do not break the requirement that burst separations be integer multiples of a single period.
- Intervals between bursts in widely separated runs can constrain longer periods, but these have been excluded for FRB 121102 on the basis of the multiple intervals observed in a single run.

PULSAR-LIKE MODELS OF FRB

- Energetics are an additional problem for pulsar-like models.
- The usual assumption that pulsars have no energy reservoir between their rotational energy, tapped at the rate of dipole radiation, and a relativistic wind and radiation field, implies extreme values of both magnetic dipole moment and rotation rate in order to explain FRB powers $\sim 10^{43}$ ergs/s.
- This combination may be impossible, and would imply very short lifetimes (Katz 2016a, 2018a)

SGR-LIKE MODELS OF FRB

- SGR-like models are attractive because of their abundant energy; the giant outburst of SGR1806-20 on December 27, 2004 released about 10^{47} ergs in about 0.1 s
- This is about seven orders of magnitude greater than energies inferred for FRB (Thornton et al. 2013)
- In addition, SGR have sub-ms rise times, consistent with the $\sim$ ms durations of FRB and shorter than any other known astronomical process other than pulsar pulses and their substructure

Theoretical Difficulties:

- Here we consider issues that arise if FRB are produced by relativistic electrons near the surfaces of neutron stars around the peaks of SGR outbursts:
- SGR appear to be thermalized sources with approximately black-body spectra at temperatures of tens or hundreds of keV, while FRB are produced by coherent non-thermal processes with brightness temperatures as high as $\sim 10^{35}$ K.

SGR-LIKE MODELS OF FRB

- The radiation environment of a SGR during the peak of its outburst is hostile to relativistic particles, such as required in many models to radiate a FRB.

Particles radiating curvature radiation at a frequency ν in a magnetic field with radius of curvature R have Lorentz factors:

$$\gamma \sim \left(\frac{\nu R}{c}\right)^{1/3} \sim 50$$

where we have taken $\nu \sim 1$ GHz and R ~ 10^6 cm, appropriate to neutron star models of FRB.

A relativistic electron of energy $E = \gamma m_e c^2$ moving through a thermal uncollimated radiation field of energy density ε suffers an energy loss by Compton scattering

$$\frac{dE}{d\ell} \sim \gamma^2 \sigma \mathcal{E},$$

where ℓ measures its path and σ is the Compton energy loss scattering cross-section (Klein-Nishina cross-section convolved with the kinematics of recoil energy loss):

SGR-LIKE MODELS OF FRB

$$\sigma \sim \left(\frac{e^2}{m_e c^2}\right)^2 \frac{\ln(E_p/m_e c^2)}{E_p/m_e c^2} \sim \left(\frac{e^2}{m_e c^2}\right)^2 \frac{\ln\gamma}{\gamma}$$

where E_p is the photon energy in the electron's frame.

- The final approximation applies to a photon with hν ~ $m_e c^2$ in the star's frame, a representative value for a black body spectrum characteristic of the giant outburst of SGR 1806-20, for which $E_p \sim \gamma m_e c^2$.

The energy loss length:

$$\ell \sim \frac{(m_e c^2)^3}{e^4 \mathcal{E} \ln\gamma} \sim 10^{-7} \left(\frac{10^{25}\ \mathrm{erg/cm^3}}{\mathcal{E}}\right) \mathrm{cm}.$$

A SGR emitting $P_{SGR} \sim 10^{48}$ erg/s (Hurley et al. 2005; Palmer et al. 2005) from the A ~ 10^{13} cm^2 surface area of a neutron star has E = 4 P_{SGR} /(A_c) ~ 10^{25} erg/cm^3 :- energy loss is extremely rapid

SGR-LIKE MODELS OF FRB

- In order to make up this energy loss by acceleration would require an electric field :

$$E_{el} \sim \frac{\gamma m_e c^2}{e\ell} \sim 10^{12}\ \mathrm{esu/cm}.$$

- Such a field cannot be realized. In vacuum it would rapidly lead to breakdown into a pair gap, as in standard pulsar theory.

Observational difficulties:

- Men et al. (2019) set upper bounds on the rate of FRB at the locations of six gamma-ray bursts suggested to house “magnetar” neutron stars.
- The failure of Tendulkar, Kaspi & Patel (2016) to detect a FRB during the observation of the great outburst of SGR 1806-20 is a strong argument against the association of FRB with SGR. The collimation of the FRB is a possible loophole to this argument.

SGR-LIKE MODELS OF FRB

The recent results of Casentini et al. (2019) make the converse argument against the association of FRB with SGR:

- The AGILE X-ray and gamma-ray satellite viewed two repeating FRB during their outbursts, and no X- or gamma-rays were observed, with upper limits ~ 2×10^{46} ergs at the distance of 149 Mpc of FRB 180916 (Marcote et al. 2020).
- This is inconsistent with an outburst like the great outburst of SGR 1806-20.

  Casentini et al. (2019)'s Source 2 at ~ 300 Mpc (an upper bound on its distance implied by its dispersion measure) is also likely inconsistent with an event like SGR 1806-20.

- This argument cannot be evaded by collimation because the thermal soft gamma-ray emission of SGR cannot be strongly collimated.

FRB SKY DISTRIBUTION

- The distribution of FRB on the sky shows no evidence of a Galactic contribution.
- In contrast, the sky distribution of fluence of every other extra-Solar System astronomical radiation of stellar origin, with the sole exception of gamma-ray bursts (GRB), is dominated by the Galactic disc. (GRB are the exception because they are rare events with large characteristic scale.)
- A FRB (or any event) at a Galactic distance of 10 kpc would be about 117 dB brighter than at cosmological ($z = 1$; luminosity distance of about 7 Gpc) distances.
- The far ($\sim 60^\circ$) side-lobe sensitivity of radio telescopes is typically about 60 dB less than their mean beam sensitivity, leaving about 57 dB of headroom for detection of Galactic micro-FRB. They would be detected, with comparable signal-processing systems, in any pulse-sensitive observation if their intrinsic strength were within five orders of magnitude of those of the observed cosmological FRB.

FRB SKY DISTRIBUTION

- The absence of detected Galactic micro-FRB implies that the Galaxy contains no objects that could emit repeating FRB.
- It argues against neutron stars as sources because there are many, with ranges of several orders of magnitude of magnetic fields, rotation rates and ages, in the Galaxy
- If neutron stars with optimal values of parameters make FRB that can be detected at $z \sim 1$, neutron stars with less optimal values of parameters should emit micro-FRB detectable at ~ 10 kpc.
- This argument does not apply to catastrophic models of FRB because in such models there are no micro-FRB (just as there are no micro-SN or micro-GRB). The FRB rate, like the GRB rate, would be so low that none would likely have occurred during the period of observations.
- Could we integrate long enough, the FRB fluence, like the GRB fluence, would be dominated by the Galactic disc. But we know that repeating FRB cannot be catastrophic.

FRB 180916.J0158+65

- The recently discovered (CHIME/FRB 2020) P = 16.35 day modulation period of FRB 180916.J0158+65 is much too long to be ascribed to the rotation of a neutron star, whose known rotation periods are $\sim 10^{-3}$–10^{3} s.
- It might be a binary orbital or superorbital (disc precession or apsidal advance) period, 10–50 times longer than the orbital period, it neither requires nor excludes a neutron star.
- The apparent absence of an analogous long period in FRB 121102 may perhaps be attributed to its comparatively few and scattered (though longer) observations, in contrast to the approximately 300 observations of FRB 180916.J0158+65 well distributed over a year (CHIME/FRB 2020).
- The confinement of bursts within about 0.3 of the period, as opposed to a smoother modulation of their rate, suggests intermittent activity in a precessing beam produced by black hole accretion (Katz, 2017), in analogy to the precession of jets in AGN

FRB 180916.J0158+65

Their possible relation to FRB is supported by:

- The inference of offset massive black holes in dwarf galaxies (Reines et al. 2020)
- The identification of FRB 121102 with a dwarf galaxy (Tendulkar et al. 2017) and
- The offset of FRB 180924 (Bannister et al. 2019) and FRB 190523 (Ravi et al. 2019) from the centers of their host galaxies.

DISCUSSION

- Neutron star models of repeating FRB are questionable
- Pulsar-like models imply periodicity that is not observed. They make energetic demands that are difficult to meet.
- SGR-like models imply periodic modulation that has not been seen. Also, no* FRB was observed in association with a Galactic SGR. SGR are excluded from association with two extragalactic FRB.
  Repeating FRB require a different explanation.
- If apparently non-repeating FRB are actually one-off, catastrophic events these arguments would not apply to them. There would need to be two different FRB mechanisms, one for repeaters and one for non-repeaters; the latter could involve the birth or death of a neutron star.

DISCUSSION

- The rarity of FRB sources implied by the absence of Galactic micro-FRB excludes stellar mass black holes as well as neutron stars
- A neutron star model might satisfy the constraint of rarity (but not that of aperiodicity) by limiting emission to the very youngest and perhaps fastest rotating or most strongly magnetized stars.
- No such loophole exists for black holes, whose properties (aside from mass and angular momentum if they are rapidly accreting) do not change with age.
  The only known objects rare enough to meet the criterion of rarity are intermediate-mass or massive black holes (Katz 2019).
- Comparison to FRB 121102 argues against attributing the absence of Galactic neutron star FRB to short active life-times.
- FRB 121102 has been active for seven years, with no apparent sign of decay; a neutron star's activity, even if decaying, would remain observable at Galactic distances very much longer than at the distance of FRB 121102 at which it would be $\sim 10^{10}$ times fainter. -

DISCUSSION

- Precession of a beam and the disc that feeds and guides it can be driven by the Lense-Thirring effect or non-relativistically by a massive surrounding disc.
- In contrast to models based on (i) free precession of a neutron star that predict a smoothly lengthening precession period as the star spins down and (ii) binary models in which orbital and precession periods are stable, models based on a precessing jet produced by black hole accretion are consistent with any trend.
- A disc remnant of a disrupted star (Nixon & King 2013) would gradually dissipate, the torque it exerts would decline, and the resulting precession period would lengthen.
- The observed (CHIME/FRB 2020) maintenance of phase stability in FRB 180916.J0158+65 to $\Delta\varphi \leq 1$ radian over an observation time t_{obs} implies a lower bound on a characteristic time scale of steady period change t_{char} ~ 20 y.
- If FRB are produced in accretion disc funnels or jets, analogous phenomena might be observable in blazars, in which these funnels and jets are directed to the observer, although their dependence on black hole mass, accretion rate and other parameters is unknown.

Thank you