Coherence constraints on physical parameters at bright radio sources and FRB emission mechanism
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ABSTRACT

We discuss physical constrains that observations of high brightness temperature coherent radio emission, with brightness temperatures as high as $T_b \sim 10^{35}$ K, impose on the plasma parameters at relativistically moving astrophysical sources. High brightness temperatures imply a minimal plasma energy density at the source. Additional important constraints come from the fact that resonantly emitting particles lose most of their energy to non-resonant inverse Compton and synchrotron processes.

We also interpret recent observations of high-to-low frequency drifting features in the spectra of repeating FRBs, FRB121102 and FRB180814, as analogues of type-III Solar radio bursts produced by reconnection plasma beams within magnetospheres of highly magnetized neutron stars.

1. Introduction

A number of astrophysical sources show high brightness temperatures, reaching, in case of pulsars and fast radio bursts (FRBs), values of $\sim 10^{35}$ K (e.g., Manchester & Taylor 1977; Melrose 2000; Lorimer et al. 2007), and as high as $\sim 10^{40}$ K in extreme cases (e.g., Soglasnov et al. 2004). These observations imply physical constraints at the emitting plasma that we discuss below.

Though high brightness bursts from Crab and other pulsars have been known for a long time (Staelin & Reifenstein 1968), recent observations of mysterious FRBs (Lorimer et al. 2007) impose new constraints on the physical properties at the source. One of the more constraining limitations come from recent identification of a repeating FRB (Spitler et al. 2016). The implied luminosity of $\sim 10^{40}$ erg s$^{-1}$, taken with short duration $\sim$ few milliseconds and large distances $\sim 1$ Gpc implies very high energy density at the source. Lyutikov (2017) (see also Lyutikov et al. (2016)) argued that these constraints limits the loci of the radio emission generation to neutron stars’ magnetospheres.

In this Letter we discuss more thoroughly what limitation on the physical parameters at the relativistically moving source (e.g., density and magnetic field) can be obtained from the the observations of high brightness radio emission. In §2 we discuss general relations, without limiting ourselves to any particular physical location, while in §3 we apply these to the neutron stars. Finally, in §4 we discuss implications of recent observations of frequency drifts in FRBs.

2. Limits on physical parameters at the sources of high brightness radio emission

2.1. Required plasma density

Most likely, the extremely high brightness temperatures in astrophysical radio sources involve relativistic plasma, so that in the center of momentum frame the spread of Lorentz factors $\gamma$ is large, $\gamma \gg 1$. Plasma is likely to be in magnetic field. In addition the center of momentum frame may move with respect to the observer with relativistic bulk Lorentz factor $\Gamma \gg 1$. 
Let’s assume that an instantaneous flux $F_\nu$, at frequency $\nu$, with variability time $\tau$ is observed from an unresolved source located at distance $d$ away. Neglecting for a moment possible bulk motion (to be accounted for later, §2.2), the (isotropic-equivalent) radiation energy density at the source is then

$$4\pi d^2 \nu F_\nu = 4\pi u_\nu c (c\tau)^2 \rightarrow u_\nu = \frac{\nu F_\nu d^2}{c^3 \tau^2} $$

(1)

The brightness temperature is defined as

$$k_B T_b = \frac{\lambda^2 F_\nu d^2}{\pi (c\tau)^2}$$

(2)

where $\lambda = \nu/c$ is the wavelength. Hence

$$k_B T_b = \frac{1}{\pi} \lambda^3 u_\nu$$

(3)

Thus, brightness temperature is approximately the energy density of radiation within a volume of wavelength cubed. This has a simple explanation for bunching/antenna mechanism, yet it is more general and applies also to plasma masers (where effective “bunching” occurs in phase space).

Radiation energy density at the source $u_\nu$ should be a fraction $\eta_\nu < 1$ of emitting particles’ energy density,

$$u_\nu = \eta_\nu \gamma n m_e c^2,$$

(4)

where $\gamma$ is the random Lorentz factor of particles at the source. (Values of $\gamma$ and $n$ refer only to the coherently emitting particles, not the total energy/density.) Hence

$$k_B T_b = \frac{\eta_\nu}{\pi} \gamma n m_e c^2 \lambda^3$$

(5)

Since $\eta_\nu \leq 1$, this puts constraints on the parameters at the source:

$$\gamma n \leq \frac{k_B T_b}{n m_e c^2 \lambda^3} = \frac{k_B T_b}{m_e c^2 V_c}$$

(6)

where we have identifies $\pi \lambda^3 \approx V_c^{-1}$, $V_c$ is a coherence volume in phase space.

Given the radiation flux and the radiation energy density (1) one can calculate the equipartition magnetic field $B_{eq}$ (Lyutikov 2017; Lyutikov et al. 2016):

$$B_{eq} = \sqrt{8\pi} \sqrt{\frac{\nu F_\nu d}{c^3 \tau^2}} = \sqrt{8\pi} \sqrt{\frac{T_b}{\lambda^3}} = 10^8 \frac{\nu}{c} T_b^{1/2} \frac{1}{10} \text{G}$$

(7)

The magnetic field (7) can occur, first of all, in the neutron star magnetospheres, but also in the magnetospheres of white dwarfs and stellar mass black holes. (See also §2.3 for the requirements on the magnetic fields at the source.)

Two basic modifications of the relationships (5-6) can be made. First, emission is likely to be anisotropic at the source, confined within solid angle $d\Omega_c$. we need to substitute $V_c \rightarrow (d\Omega_c/(4\pi)) V_c$. Second if internal emission is narrowband (so that at the detector it produces fractional bandwidth $f_\nu = \Delta \nu / \nu$, where $\nu$ is the center frequency and $\Delta \nu$ is the emission band), then $V_c \rightarrow f_\nu V_c$. Thus, overall, $V_c \approx (d\Omega_c/(4\pi)) f_\nu \lambda^{-3}$ and condition (6) becomes

$$\gamma n \leq f_\nu \frac{\Omega_c}{4\pi} \frac{k_B T_b}{n m_e c^2 \lambda^3}$$

(8)

Given the uncertainties of the problem, we will further omit these complications.
2.2. Relativistically moving variable sources

If the source of emission is moving relativistically with Lorentz factor $\Gamma$ (and the corresponding Doppler factor with respect to the observer $\delta$), and varies with a time scale $\tau'$ in the plasma rest frame, then using Lorentz transformations

\[
F_\nu = \delta^3 F'_\nu \\
\nu' F'_\nu = \delta \nu \nu F' \nu \\
\nu' \propto \delta \nu' \\
\tau = \delta^{-1} \tau' \\
n = \Gamma n' \\
T_b = \delta^3 T'_b
\]

(primes denote quantities measured in the plasma rest frame), we find

\[
u'_r = \frac{(\nu F'_\nu) q^2 c^3}{\delta^2}
\]

(10)

Hence

\[k_B T_b = \eta_r \gamma \lambda^3 m_e c^2 n' \delta^4
\]

(11)

Or

\[\gamma \delta^4 n' > \frac{k_B T_b}{m_e c^2 \lambda^3}
\]

(12)

Expression (12) is a requirement on internal plasma parameters, $\gamma$ and $n'$, and bulk motion Doppler factor $\delta$ in terms of the observed brightness temperature $T_b$ and wavelength $\lambda$.

Inverting (12), we can put a limit on the highest possible frequency where coherent emission of given brightness $T_b$ can be observed:

\[\nu_c \leq \left( \frac{m_e n' e^5}{k_B T_b} \right)^{1/3} \gamma^{1/3} \delta^{4/3}
\]

(13)

Using definition of the brightness temperature this translates to

\[\nu_c \leq \frac{n' m_e e^5 \tau^2}{q^2 F'_\nu} \gamma \delta^4
\]

(14)

We stress that $n'$ is the plasma (emitting leptons') density in the rest frame; in the observer frame $n = \Gamma n'$.

If the plasma is moving along magnetic field, the estimate (7) remains valid in the plasma rest frame. (Otherwise $B' = B/\Gamma$). This immediately implies that $\sim 10^{35}K$ brightens temperatures must come from neutron stars' magnetospheres. Also note that the equipartition magnetic field is the lower estimate on the magnetic field at the source, so that we can parametrize $B = b_{eq} B_{eq}$ with $b_{eq} \geq 1$.

Using parametrization of the magnetic field at the source (7) and the enthalpy density $\approx \gamma n' m_e c^2$, the magnetization parameter $\sigma$ (Kennel & Coroniti 1984) is

\[\sigma = \frac{B^2}{4\pi \gamma n' m_e c^2} \approx \eta_r b_{eq}^2 \delta^4
\]

(15)

In a relativistic plasma we expect $\sigma \geq 1$. This requires super-equipartition magnetic field $b_{eq} \geq 1$ and/or Doppler motion $\delta \geq 1$, and not highly matter dominated regime, $\eta_r$ not too small.
2.3. Nonlinearity/intensity parameter $a$

The electromagnetic wave intensity parameter evaluates to

$$a \equiv \frac{eE'}{2\pi n_e c \nu'} = \frac{e\sqrt{\nu k_B T_b}}{m_e c \nu' \delta} = 3 \times 10^5 \nu_{GHz}^{1/2} T_b^{1/2} \delta^{-1}$$

(E' is the electric field of the wave in the rest frame). Parameter $a$ is a dimensionless transverse momentum of a particle in the electromagnetic wave.

If a particle oscillates in the electromagnetic fields of the coherent wave with amplitude $a$, then in addition to the energy losses to the emission of coherent waves it will also suffer Inverse Compton (IC) and synchrotron losses (if magnetic field is present). Typically those “normal” losses will dominated over the “coherent” losses. For example, if an external magnetic field is present, the particle will also emit synchrotron radiation. The synchrotron radiation decay times become shorter than pulse duration in the plasma frame for

$$T_b \geq \frac{1}{k_B e^{1/3} \nu^{4/3} \delta^{2/3}} = 10^{29} b_{eq}^{-4/3} \nu_{GHz}^{-7/3} \delta^{-2/3} \tau^{-2/3} \text{K}$$

For brightness temperatures exceeding (17) the coherent electromagnetic wave cannot be sustained. In case of IC losses, the estimate (17) remains valid with $b_{eq}$ set to unity.

There is an important caveat to the above statement. In larger magnetic fields, with $\omega_B \geq 2\nu'$ where $\omega_B = eB/(m_e c)$ and $\nu'$ is the wave frequency in the source frame, the nature of the particle’s motion in the field of the electromagnetic wave changes: instead of fast acceleration in the electric field of the wave a particle experiences slow drift with velocity $v_d/c \sim E'/B$ (here $E'$ is the electric field of the wave, while $B$ is the external magnetic field). This condition translates to

$$T_b \geq \frac{1}{k_B e^{2/3} \delta^{2/3} b_{eq}^2} = 5 \times 10^{23} b_{eq}^{-2} \nu_{GHz}^{-1} \delta^{-2} \text{K}$$

It is easily satisfied for the observed brightness temperatures. Thus, the presence of high magnetic fields in high brightness relativistic sources is required to avoid large radiative losses of coherently emitting particles to IC and synchrotron processes.

3. Neutron stars’ magnetospheres

The relations derived above involve the source number density $n'$ and Lorentz factors $\gamma$ and $\Gamma$. To proceed further we can parametrize the number density to the expected ones, particularly in the case of neutron star magnetospheres. Two parameterizations are possible: (i) pulsar-like, normalizing the rest frame density to the GJ density (Goldreich & Julian 1969)

$$n_{\text{pulsar}}' = \kappa \frac{\Omega B}{2\pi c \epsilon \Gamma}$$

where $\kappa \sim 10^3 - 10^6$ is the observer frame multiplicity (Fawley et al. 1977; Timokhin 2010) and $\Omega$ is the neutron star spin; and (ii) magnetar-like (Thompson et al. 2002)

$$n_{\text{magnetar}}' = \Delta \phi \frac{B}{2\pi c \epsilon \Gamma}$$
(the last comes from equating \( \text{curl} B \sim \Delta \phi B / r \) to \( (4\pi/c)2\eta c \), \( \Delta \phi \) is a typical twist angle in the magnetosphere.)

For pulsar-like parametrization (19) the condition (12) gives

\[
\eta_{r} = \frac{r_{e}kBT}{\kappa\gamma^{3}\Omega B_{m}m_{e}^{\Gamma}}
\]

\[
\kappa\gamma^{3} > \frac{r_{e}kBT}{\lambda^{3}\Omega B_{m}m_{e}} = 5 \times 10^{18} \nu_{GHz}^{3} P_{0}^{4} T_{b,35}^{-1} \left( \frac{R}{R_{LC}} \right)^{3}
\]

where we estimated \( \delta \sim 2\Gamma \) and normalized to period \( P_{0} = \text{one second}; \) \( R_{LC} = c/\Omega \) is the light cylinder radius. In the extreme case, a millisecond pulsar with quantum magnetic field producing radiation near the light cylinder, it is required that

\[
\kappa\gamma^{3} > 6 \times 10^{6} T_{b,35}
\]

This is not too containing, since we expect \( \kappa \sim 10^{3} - 10^{6} \) and \( \gamma \sim \Gamma \sim 10^{3} - 10^{4} \) (e.g., Hibschman & Arons 2001; Timokhin 2010).

Similarly, for Crab giant pulses

\[
\kappa\gamma^{3} > 3 \times 10^{13} \nu_{GHz}^{3} \left( \frac{r}{R_{LC}} \right)^{3} T_{b,35}
\]

which can be accommodated with the assumed multiplicity and Lorentz factors even at the light cylinder.

For (millisecond) magnetar-like parametrization (20), the condition (12) gives

\[
\gamma^{3} \geq \frac{\varepsilon\nu^{3}kBT}{m_{e}c^{3}Bm_{B}^{2}} = 10^{7} \nu_{GHz}^{3} \left( \frac{P}{10^{-3}\text{sec}} \right)^{4} T_{b,35} \left( \frac{B}{B_{Q}} \right)^{-1} \left( \frac{r}{R_{LC}} \right)^{4}
\]

Which can also be accommodated with \( \gamma \sim \Gamma \sim \text{few hundred}.\)

Finally, the ratio of the local magnetic field to the equipartition magnetic field (7) evaluates to

\[
b_{eq} = \frac{B_{NS}(r/R_{LC})^{3}}{B_{eq}} = 3 \times 10^{5} \left( \frac{B_{NS}}{B_{Q}} \right)^{-3/2} \nu_{GHz}^{3/2} \left( \frac{r}{R_{LC}} \right)^{-3} T_{b,35}^{-1/2}
\]

where \( B_{Q} = 4 \times 10^{13} \text{ Gauss} \) is the quantum critical magnetic field. Though Eq. (25) has a number of unknown parameters, there is a large region of allowed \( b_{eq} \geq 1.\)

4. Frequency drifts in FRBs - magnetar magnetospheres?

Two FRBs show similar features in their dynamic spectra: FRB121102 (Hessels et al. 2018) and FRB180814 (Amiri et al., 2019a,b, Nature). The spectrum consists of narrow frequency bands drifting with time down in frequency. The similarity in two cases may hint at the physical origin of the emission, though such behavior was not seen universally. Alternatively, spectral drifts are expected in the lensing scenarios (Cordes et al. 2017), though in that case both upward and downward drifts are expected. Two examples of downward drift make a case against lensing, though a weak one at the moment.

First, we interpret similar frequency behavior as an indication of a some kind of a stiff confining structures - most likely the magnetic field. Narrow spectral features could then be related to the local plasma parameters (e.g., plasma and cyclotron frequencies). Frequency drift then reflects the propagation of the emitting region in changing magnetospheric
conditions, similar to what is called “radius-to-frequency mapping” in pulsar research (e.g., Manchester & Taylor 1977; Phillips 1992).

The frequency drift in FRBs is also reminiscent of type-III Solar radio bursts, whereby narrow frequency features show high-to-low temporal evolution (e.g., Fainberg & Stone 1974). Interestingly, type-III Solar radio bursts show temporal behavior, intensity \( \propto t^{-1} \) (Fig. 5 and Fig. 6 in Fainberg & Stone 1974) which is similar to the observed behavior in FRBs Hessels et al. (2018) and (Amiri et al., 2019a,b, Nature).

Even before the discovery of radio emission from magnetars Lyutikov (2002) (see also Eichler et al. 2002) suggested that magnetar radio emission will be (is) different from pulsar emission - it is magnetically powered in magnetars, similar to solar flares - as opposed to rotationally powered in the case of pulsars. Lyutikov (2002) also argued that, quote, “one may expect the frequency drift of the peak of radio emission, characteristic of type III bursts”. With a due uncertainty (that this prediction was not confirmed in magnetars and that not all FRBs show this behavior) we consider observations of drifting narrow band emission in FRBs as pointing to reconnection-driven plasma processes in magnetar magnetospheres.

Type-III Solar radio bursts arise due to conversion of Langmuir waves into escaping modes (e.g., Zheleznyakov & Zaitsev 1970). The Langmuir waves, in turn, are excited by electron beams, presumably generated at reconnection sites. Applications of these ideas to pulsars were thoroughly investigated in the early days of pulsar research, but with no firm conclusion (e.g., Ruderman & Sutherland 1975; Asseo et al. 1990, and reference there in). (See Melrose (2000) for critical review of pulsar radiation theory). One of the biggest limitations in case of pulsars was a slow growth rate of Langmuir instabilities. Qualitatively, effective parallel mass scales as \( \gamma^3 \) (hence it is hard to accelerate relativistic particle along the direction of its motion), and bulk relativistic motion expected on the open field lines of pulsar magnetospheres further increases demands on the growth rate of pure Langmuir instability (Lyutikov 1999).

Reconnection-driven beams in magnetars magnetospheres though may have different physical conditions than on the open field lines of pulsars’ magnetospheres. First, the density is not limited to the Goldreich-Julian value (19) and can be much higher (20). Magnetic field at the source may be higher than in pulsars (both estimates of plasma densities increase with magnetic field). Finally, the bulk Lorentz factor may be smaller than on the open field lines of pulsar magnetospheres.

For example, if the growth rate is on plasma frequency in the plasma rest frame, \( \sim \omega_p/\sqrt{\gamma} \), the condition of fast growth in the lab frame \( \omega_p'/\Gamma \geq \Omega \) translates to

\[
\kappa \geq \gamma^{3} \frac{\Omega \sqrt{B}}{\omega_p} \approx 10^{-15} \Gamma^{3} \left( \frac{8B_{N S} \omega_p}{Q} \right)^{-1} \left( \frac{P}{10^{-3} \text{sec}} \right)^{2} \left( \frac{r}{r_{LC}} \right)^{3} , \text{for scaling (19)}
\]

\[
\Delta \phi \geq \gamma^{3} \frac{\omega_p}{\omega_p} \approx 10^{-15} \Gamma^{3} \left( \frac{8B_{N S} \omega_p}{Q} \right)^{-1} \left( \frac{P}{10^{-3} \text{sec}} \right)^{2} \left( \frac{r}{r_{LC}} \right)^{3} , \text{for scaling (20) (26)}
\]

Both these constraints can generally be satisfied in neutron stars magnetospheres. (Same numerical factor in front of expressions in (26) is due to the fact that at millisecond periods both estimates of density (19) and (20) coninside.)

A merger of two Langmuir waves with frequency \( \sim \omega_p'/\sqrt{\gamma} \) in the plasma frame will produce observed radiation at

\[
\omega \sim \Gamma \frac{\omega_p'}{\sqrt{\gamma}} = \left\{ \begin{array}{ll} 
\left( e^{\Omega \omega_p B} \right)^{1/2} = 3 \times 10^{11} \left( \frac{\omega_p}{\Gamma} \right)^{1/2} \left( \frac{B_{N S} \omega_p}{Q} \right)^{1/2} \left( \frac{P}{10^{-3} \text{sec}} \right)^{-2} \left( \frac{r}{r_{LC}} \right)^{-3/2} \text{rad s}^{-1} , \text{for scaling (19)} \\
\left( \Delta \phi \frac{\omega_p}{\omega_p} \right)^{1/2} \left( \Delta \phi \frac{\omega_p}{\omega_p} \right)^{-1/2} = 3 \times 10^{11} \left( \Delta \phi \frac{\omega_p}{\omega_p} \right)^{1/2} \left( \frac{B_{N S} \omega_p}{Q} \right)^{1/2} \left( \frac{P}{10^{-3} \text{sec}} \right)^{-2} \left( \frac{r}{r_{LC}} \right)^{-2} \text{rad s}^{-1} , \text{for scaling (19)} \end{array} \right.
\]

Both these estimates can generally produce emission at the observed radio wavelengths.

The emission frequencies (27) demonstrate downward frequency drift as an emitting entity propagates up in the
neutron star magnetosphere. For dipolar magnetic field $\propto r^{-3}$, the scalings are $\omega \propto t^{-3/2}$ and $\omega \propto t^{-2}$ for the two cases (assuming constant Doppler factor; for time-varying Doppler factor $t \to t/\delta(t)^2$).

Above derivations of emission properties are surely order-of-magnitude estimates, and are bound to be limited in their simplicity, as pulsar research showed for similar estimates in case of pulsars. Still, they demonstrate that there is a genuine possibility in relating FRB emission mechanism to Solar radio flares. (Models of Solar type-III bursts have theoretical problems on their own, e.g., the so called Sturrock’s dilemma, Sturrock (1964).) We foresee that the non-linear plasma waves conversion processes in strong magnetic field might produce escaping electromagnetic waves (e.g., Mikhailovskii & Suramlishvili 1984; Melikidze & Pataraia 1984).

Let us next list a few observational arguments for and against associating FRBs with magnetar flares. Coherent radio emission can be produced at the initial stage of a “reconnection flare”, whereby coherent “kinetic jets” of particles are generated, like the ones in the studies of Crab flares (e.g., Cerutti et al. 2014; Lyutikov et al. 2017, 2018). But there are observational constraints: (i) the SGR 1806 - 20 flare had peak power of $10^{47}$ erg s$^{-1}$ (Palmer et al. 2005) but was not seen by Parkes radio telescope (Tendulkar et al. 2016); that puts an upper limit on radio-to-high-energy efficiency $\lesssim 10^{-6}$. For the Repeater, the first Repeater, the implied high energy luminosity would be then $\gtrsim 10^{47}$ erg s$^{-1}$. On the other hand, if the Repeater was in our Galaxy the corresponding fluxes would be in GigaJansky, which are clearly not seen. Also in case of PSR J1119-6127 magnetar-like X-ray bursts seem to suppress radio emission (Archibald et al. 2017), but this is probably related to rotationally-driven radio emission, not reconnection-driven.. Thus, only some special types of magnetars can produce FRBs.

5. Discussion

In this paper we discuss the constraints on the properties of coherent emitting astrophysical sources, having in mind relativistic objects like pulsars and, presumably, FRBs. Several lines of reasoning point to neutron stars’ magnetospheres as the origin of the high brightness emission (this is of course known for pulsars, but is important for FRBs).

An important point, besides the estimates of plasma parameters at the source for given observed brightness, is the estimate of non-coherent energy losses, §2.3. Let us discuss this important argument. Particles at the source lose energy to emission of coherent (resonant) waves and, in addition, to non-resonant interactions (e.g., IC and synchrotron). Typically, the part of the energy that goes to coherent (low frequency - radio) emission is much smaller than the one going to non-resonant interactions (often in optical and X-rays). This was not much of a problem before the identification of FRBs at cosmological distances - the radio emission was always energetically unimportant, subdominant part. For example, even the brightest and rarest giant pulses from Crab reach only $10^{-2}$ of the total spin-down luminosity. Observations of FRBs, raise the bar, so to say. The implied radio luminosity is some five to nine orders of magnitude larger that is seen in pulsars (In Crab the average radio power is $\sim 10^{32}$ erg s$^{-1}$, the peak is $\sim 10^{36}$ erg s$^{-1}$; the FRB Repeater is at $\sim 10^{44}$ erg s$^{-1}$). These are macroscopically (in astrophysical sense) important powers (Lyutikov 2017) and thus do offer, for the first time from radio observations, a meaningful physical constraints on the plasma parameters at the source. We demonstrated that though these constraints are important, they can be realistically satisfied.

In conclusion, FRB emission properties point to magnetospheres of neutron stars as the origin. Two types of mechanisms can be at work - rotationally or magnetically powered. Rotationally-powered FRB emission mechanisms (e.g., as analogues of Crab giant pulses Lyutikov et al. 2016) are excluded by the localization of the Repeating FRB at $\sim 1$ Gpc (Spitler et al. 2016), as discussed by Lyutikov (2017). magnetically-powered emission has some observational constraints, as discussed at the end of §4, but remains theoretically viable.
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REFERENCES

Archibald, R. F., Burgay, M., Lyutikov, M., Kaspi, V. M., Esposito, P., Israel, G., Kerr, M., Possenti, A., Rea, N., Sarkissian, J., Scholz, P., & Tendulkar, S. P. 2017, ApJ, 849, L20
Asseo, E., Pelletier, G., & Sol, H. 1990, MNRAS, 247, 529
Cerutti, B., Werner, G. R., Uzdensky, D. A., & Begelman, M. C. 2014, Physics of Plasmas, 21, 056501
Cordes, J. M., Wasserman, I., Hessels, J. W. T., Lazio, T. J. W., Chatterjee, S., & Wharton, R. S. 2017, ApJ, 842, 35
Eichler, D., Gedalin, M., & Lyubarsky, Y. 2002, ApJ, 578, L121
Fainberg, J., & Stone, R. G. 1974, Space Sci. Rev., 16, 145
Fawley, W. M., Arons, J., & Scharlemann, E. T. 1977, ApJ, 217, 227
Goldreich, P., & Julian, W. H. 1969, ApJ, 157, 869
Hessels, J. W. T., Spitler, L. G., Seymour, A. D., Cordes, J. M., Michilli, D., Lynch, R. S., Gourdji, K., Archibald, A. M., Bassa, C. G., Bower, G. C., Chatterjee, S., Connor, L., Crawford, F., Deneva, J. S., Gajjar, V., Kaspi, V. M., Keimpema, A., Law, C. J., Marcote, B., McLaughlin, M. A., Paragi, Z., Petroff, E., Ransom, S. M., Scholz, P., Stappers, B. W., & Tendulkar, S. P. 2018, arXiv e-prints
Hibschman, J. A., & Arons, J. 2001, ApJ, 560, 871
Kennel, C. F., & Coroniti, F. V. 1984, ApJ, 283, 694
Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, Science, 318, 777
Lyutikov, M. 1999, Journal of Plasma Physics, 62, 65
—. 2002, ApJ, 580, L65
—. 2017, ApJ, 838, L13
Lyutikov, M., Burzawa, L., & Popov, S. B. 2016, MNRAS, 462, 941
Lyutikov, M., Komissarov, S., & Sironi, L. 2018, Journal of Plasma Physics, 84, 635840201
Lyutikov, M., Sironi, L., Komissarov, S. S., & Porth, O. 2017, Journal of Plasma Physics, 83, 635830601
Manchester, R. N., & Taylor, J. H. 1977, Pulsars
Melikidze, G. I., & Pataraya, A. D. 1984, Astrofizika, 20, 157
Melrose, D. B. 2000, in Astronomical Society of the Pacific Conference Series, Vol. 202, IAU Colloq. 177: Pulsar Astronomy - 2000 and Beyond, ed. M. Kramer, N. Wex, & R. Wielebinski, 721–+

Mikhailovskii, A. B., & Suramlishvili, G. I. 1984, Astrophysics, 20, 314

Palmer, D. M., Barthelmy, S., Gehrels, N., Kippen, R. M., Cayton, T., Kouveliotou, C., Eichler, D., Wijers, R. A. M. J., Woods, P. M., Granot, J., Lyubarsky, Y. E., Ramirez-Ruiz, E., Barbier, L., Chester, M., Cummings, J., Fenimore, E. E., Finger, M. H., Gaensler, B. M., Hullinger, D., Krimm, H., Markwardt, C. B., Nousek, J. A., Parsons, A., Patel, S., Sakamoto, T., Sato, G., Suzuki, M., & Tueller, J. 2005, Nature, 434, 1107

Phillips, J. A. 1992, ApJ, 385, 282

Ruderman, M. A., & Sutherland, P. G. 1975, ApJ, 196, 51

Soglasnov, V. A., Popov, M. V., Bartel, N., Cannon, W., Novikov, A. Y., Kondratiev, V. I., & Altunin, V. I. 2004, ApJ, 616, 439

Spitler, L. G., Scholz, P., Hessels, J. W. T., Bogdanov, S., Brazier, A., Camilo, F., Chatterjee, S., Cordes, J. M., Crawford, F., Deneva, J., Ferdman, R. D., Freire, P. C. C., Kaspi, V. M., Lazarus, P., Lynch, R., Madsen, E. C., McLaughlin, M. A., Patel, C., Ransom, S. M., Seymour, A., Stairs, I. H., Stappers, B. W., van Leeuwen, J., & Zhu, W. W. 2016, Nature, 531, 202

Staelin, D. H., & Reifenstein, III, E. C. 1968, Science, 162, 1481

Sturrock, P. A. 1964, NASA Special Publication, 50, 357

Tendulkar, S. P., Kaspi, V. M., & Patel, C. 2016, ApJ, 827, 59

Thompson, C., Lyutikov, M., & Kulkarni, S. R. 2002, ApJ, 574, 332

Timokhin, A. N. 2010, MNRAS, 408, 2092

Zheleznyakov, V. V., & Zaitsev, V. V. 1970, Soviet Ast., 14, 250

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