IS COHERENCE ESSENTIAL TO ACCOUNT FOR PULSAR RADIO EMISSION?

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ABSTRACT

Based on definitions, two joint-criteria, namely, the optical-thin constraint and the energy budget constraint, are proposed to judge whether the emission nature of radio pulsars is incoherent or obligatory to be coherent. We find that the widely accepted criterion, i.e. $kT_B \leq \epsilon$, is not a rational criterion to describe the optical-thin condition, even for the simplest case. The energy budget constraint could be released by introducing a certain efficient radiation mechanism (e.g. the inverse Compton scattering, QL98) with emission power of a single particle as high as a critical value $P_{\text{sing},c} \sim 10^{-4} - 10^{-3}\text{erg} \cdot \text{s}^{-1}$. This in principle poses the possibilities to interpret high luminosities of pulsars in terms of incoherent emission mechanisms, if the optical-thin constraint could be released by certain mechanism as well. Coherence may not be an essential condition to account for pulsar radio emission.

Subject headings: pulsar: general - radiation mechanism: non-thermal

1. INTRODUCTION

Shortly after the discovery of the first pulsars, the question why they pulsate is soon answered in terms of rapid spin of the magnetized neutron stars. Another fundamental question why they shine, however, is not fully answered till today, after 30 years. The key problem lies in the observed high brightness temperatures of pulsar emissions, which are commonly thought to be due to certain coherent radiation mechanisms (Ginzburg, Zheleznyakov & Zaitsev, 1969, hereafter GZZ69; Ginzburg & Zheleznyakov 1975; Melrose 1992a,b, hereafter M92a,b). Various coherent mechanisms have been proposed to interpret the nature of pulsar emission (for reviews, see e.g. Ginzburg & Zheleznyakov 1975; M92a,b).

Here we'll re-investigate the fundamental question whether coherence is an obligatory condition for any promising emission model of radio pulsars. We'll show that the widely adopted criterion, i.e. $kT_B \leq \epsilon$, (1)

where $T_B$ is the brightness temperature of radiation, $\epsilon = (\gamma - 1)mc^2$ is the kinetic energy of the relativistic particles, is not a rational criterion to judge whether a radiation mechanism is obligatory to be “coherent”. We'll put forward two joint-criteria by definitions instead and show how severe these constraints are on any incoherent mechanism.

2. WHAT'S THE KEY CRITERION TO JUDGE THE COHERENT NATURE OF PULSAR EMISSION?

2.1. Incoherent and coherent emission

According to M92a, there is no general definition of the so-called “coherent” emission, while a working definition is “any non-thermal emission that cannot be explained in terms of incoherent emission”. For an incoherent mechanism, it is defined as that “the intensity (or luminosity) of radiation from the source is less or equal to the sum of the intensities of spontaneous emission from different parts of the source” (GZZ69), and as “due to spontaneous emission when the corresponding absorption process is unimportant” (M92a). From these definitions, we come to two inequations as the constraints of any incoherent emission, which read

$$\tau = \int_0^\infty \alpha_\nu d\nu \leq 1,$$  (2a)

and

$$P_{\text{sing}}nl^2s \geq L_{\text{obs}}.$$  (2b)

The constraint [2a] is to define that “absorption process is unimportant", in which $\alpha_\nu$ is the absorption coefficient, $\tau$ is the optical-depth of the radiation produced in the inner magnetosphere which travels an escaping distance $s_e$ to out of the magnetosphere. We also define $s_0$ as the upper limit of $s_e$ defined by $\tau = 1$, which is the “transparent” distance of the radiation. We call [2a] the “optical-thin constraint”. The next constraint [2b] is to show that the sum of the emission power from individual particles (i.e. $P_{\text{sing}}$) could meet the total emission power (i.e. luminosity $L_{\text{obs}}$) observed, which we call the “energy budget constraint”. Here $n$ is the number density of the particles who contribute to the luminosity, and the volume is adopted as $l^2s$, where $l$ is the typical extended scale of the source and $s$ is the depth of the emission region. Note $s \leq s_0$, since emission deeper that the “transparent” depth $s_0$ can not escape from the magnetosphere (see [2a]). Any violation of the either constraint above will make an incoherent emission failed to interpret the observed emission from pulsars.

Generally, people tend to think that the high brightness temperatures inferred from pulsar observations have made both constraints failed, which means that one has to appeal to certain coherent mechanisms. The earliest

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idea of coherent mechanism is to solve the “energy budget” problem by introducing the “bunching” mechanism (e.g. Ruderman & Sutherland 1975). This will enhance the emission power of an individual particle to a factor of $N$, where $N$ is the number of the particles in the bunch. Such a mechanism was later criticized both about its origin and its maintenance (Melrose 1978; hereafter M78; M92a,b). Furthermore, it was argued that such a coherent mechanism still fails to fulfill the “optical-thin” condition [2a] provided the typical brightness temperatures inferred from pulsars (M78). To release the optical-thin constraint, usually certain “maser” (negative absorption) mechanisms are proposed. In the maser models, the optical depth becomes negative so that [2a] is well satisfied, and the “amplification” effect due to population reverse of the energy levels can meet the energy budget requirement. The problems in these models, however, lie in that there is no simple form of curvature maser mechanism to operate, and that more complicated forms are apparently in contradiction to certain observational or “inferred” facts. For example, maser curvature emission including curvature drift (Luo & Melrose 1992) rules out the possible emission from the millisecond pulsars, while the fact is that there is no distinct difference between the emission features of millisecond pulsars and those of normal pulsars (Manchester 1990). The third group of the coherent mechanisms are the even more complicated forms of “indirect” emissions by invoking “hydrodynamic instabilities” (e.g. Beskin, Gurevich, & Istomin 1988; Kazbegi, Machabeli, & Melikidze 1991), some forms of which are regarded as the “most plausible” mechanisms (M92b).

### 2.2. Is $k T_B \leq \epsilon$ a rational criterion to judge the coherent nature of the source?

The point which drives people thinking that coherence is essential is the widely adopted criterion [1] (e.g. GZZ69; M92a, b; Luo 1998) rather than criteria [2a,b]. According to [1], to achieve the observed high brightness temperatures of pulsars (typically $10^{27}K$ at 400 MHz, Sutherland 1979; also see eq.[3] below) with an incoherent process, the Lorentz factor of the particles should be as high as $\gamma - 1 \geq 1.7 \times 10^{17}T_{B,27}$, which is unachievable in various pulsar polar cap models due to the limitation of the inner accelerators by the $\gamma - B$ (e.g. Sturrock 1971; Ruderman & Sutherland 1975; Arons & Scharlemann 1979; Usov & Melrose 1996; Zhang et al. 1997a; Harding & Muslimov 1998) or $\gamma - \gamma$ (Zhang & Qiao 1998) absorption of the $\gamma$-rays. In other words, for a certain $\gamma$ of the particles, the brightness temperature is constrained to $T_B \leq 5.9 \times 10^9K$. This leads to the conclusion that any emission model must appeal to certain coherent mechanisms. Here we’ll re-investigate the validity of eq.[1] and show that it is not a rational criterion.

The so-called brightness temperature $T_B$ of a certain object is defined as the effective temperature of a black-body whose emission intensity at a certain frequency is just equal to the observing intensity of the object at that frequency. In the Rayleigh-Jeans regime which is viable for pulsar radio emissions, the brightness temperature reads $T_B = (c^2/2\pi k^2)I_\nu$ (Rybicki & Lightman 1979), where $k$ is the Boltzmann’s constant, $I_\nu$ is the radiation intensity at the frequency $\nu$. Connecting $I_\nu$ with direct observables, i.e. the flux $F_\nu = I_\nu \Delta\Omega$ (in unit of mJy) and distance $d$ (in unit of kpc), where $\Delta\Omega = l^2/d^2$ is the solid angle the source opens to the telescope, and again $l$ is the extended scale of the source region with typical value of $10^6 cm$ (Manchester & Taylor 1977; Lesch et al. 1998), we come to

$$T_B \simeq 3.1 \times 10^{23}K \gamma^{-2}F_\nu (\text{mJy}) d^2 (\text{kpc}) l_0^2,$$

where $l_0$ is $l$ in unit of $10^6 cm$, and $\nu_0 = \nu$ in unit of GHz. Note this temperature is different from the antenna temperature of the telescope when $\Delta\Omega$ is smaller than the beam solid angle of the telescope $\Delta\Omega_A$, which is usually the case for pulsars. Thus eq.[3] is a pure theoretical value irrelevant to the telescope details. We see this temperature is very high, and even higher for lower frequencies (e.g. 400 MHz).

The criterion [1] directly comes from the study of synchrotron self-absorption sources. However, it was not proved in the case of pulsars to our best knowledge. According to M92a, eq.[1] is the result of the limitation of self-absorption, thus it might be a variant of condition [2a]. Under the isotropic condition, the absorption coefficient can be deduced as

$$\alpha_\nu = \frac{p+2}{p} \frac{c^2}{8\pi k^2} \int d\epsilon P(\nu, \epsilon) \frac{N(\epsilon)}{\epsilon}$$

under the condition of $h\nu \ll \epsilon$, where energy-dependent particle density $N(\epsilon)$ has a power law distribution with index $p$, and $P(\nu, \epsilon)$ is the spectral emission power of the particle with energy $\epsilon$ (Rybicki & Lightman 1979, their eq.[6.52]). Adopting a very simple form of $p = 1$ and $N(\epsilon) = n/\epsilon$, and submitting them to eq.[2a], we get a dimensional analysis estimate limit as $(3/8\pi)(c^2/\nu^2)P_{nu}s \Delta\nu \leq \epsilon$. Note the luminosity $L_{\Delta\nu} = (4\pi f)F_\nu d^2 \Delta\nu = P_{nu}n^2 s \Delta\nu$, where $(4\pi f)$ is the beaming factor of the emission ($f = 1$ for isotropic emission), again using $T_B = (c^2/2\nu^2k)I_\nu$, the inequality [2a] finally turns out to be

$$k T_B \leq (\epsilon/3f).$$

Note [1'] is identical with [1] only when $f \sim 1$, i.e., for isotropic radiation. This could be the case of a synchrotron self-absorbed source, but never true for the case of pulsars which has $f \ll 1$. This means that even adopting an isotropic absorption formula as [4], and for the simplest case, eq.[1] is not a rational criterion at all.

### 2.3. Optical-thick or optical-thin?

Though [1'] sets a less stringent constraint to the achievable brightness temperature than [1] does, it does not release the optical-thin constraint, since high beaming effect (small $f$ or small $l$) also raises the inferred value of $T_B$ (see eq.[3]). However, we suppose that when we present explicit studies on more detailed mechanisms, the constraint [2a] using [4] could come to much different results than [1']. Furthermore, even eq.[4] may not be true when considering the complicated situation (e.g. anisotropic and far-from-equilibrium) in pulsar magnetospheres (see below). Thus in judging whether coherence is obligatory for a certain mechanism, we have to always go back to criteria [2a,b]. Neither [1] nor [1'] make much sense.

From the observational point of view, it seems like that pulsar magnetospheres might be optical-thin. Clear beam
"radius-to-frequency mapping" has long been observed from the multi-frequency observations (e.g. Rankin 1983), which means that we have observed different "depth" in the pulsar magnetospheres. It is hardly believable that most pulsar emissions are buried inside the optical-thick layers, while only a small portion on the surface layer escapes.

One can argue that such a optical-thin feature could be the result of certain maser (or other forms of) coherent mechanisms. However, we see that constraint [2a], which requires \( \tau \leq 1 \), still leaves much room to solve the problem without invoking any maser mechanisms which requires \( \tau < 0 \). Though proposing such a detailed optical-thin incoherent theory is beyond the scope of this paper, we present here some criticisms on the present studies on the absorption processes in pulsar magnetospheres. These comments are quite preliminary, but nevertheless some possibilities to solve the optical-thin problem within the framework of "incoherent" emission mechanisms. We hope these ideas could promote more profound studies in this area. First, almost all the studies on the self-absorption processes in pulsar magnetospheres have inherited the formalism derived from the stellar atmospheres, which is in isotropic condition (see [4]). The intense magnetic fields in pulsar magnetospheres, however, have destroyed such isotropy so that the particle motion is essentially one-dimensional as the particle is bound to the lowest Landau state. As a result, the photon field also have a preferred emission direction along the field line and particles are usually interacting with the photons tail-on. Thus absorption should be angle-dependent, which might lead to quite different results than eq.[4]. Another point is that the situation in pulsar magnetosphere is far from equilibrium, while the formalism people tend to use are derived from near-equilibrium regime. Some possible non-linear effect may be able to solve the optical-thin problem.

2.4. Energy budget

Suppose constraint [2a] could be released by introducing certain incoherent mechanism, is coherent still obligatory by constraint [2b]? Let’s express [2b] in a more obvious way.

The luminosity \( L_{\Delta \nu} \) in a certain frequency band \( \Delta \nu \) can be expressed in direct observables by

\[
L_{\Delta \nu} \simeq 9.5 \times 10^{25} \text{erg} \cdot \text{s}^{-1} (4\pi f) F_{\nu} (\text{mJy}) d^2 (\text{kpc}) \Delta \nu. \tag{5}
\]

This defines a critical value of the emission power of a single particle \( P_{\text{sing,c}} \) from \( L_{\Delta \nu}/n^2 \). Assuming the particle number density is \( n = \rho_{\text{GJ}} \), where \( \rho_{\text{GJ}} \simeq (\Omega B/2\pi c) \simeq 7.0 \times 10^{10} \text{cm}^{-3} B_{12}^{-1} \) is the Goldreich-Julian density of pulsar magnetosphere (Goldreich-Julian 1969) and \( \xi \) is the multiplicative factor due to the pair cascades, this critical power turns out to be

\[
P_{\text{sing,c}} \simeq 1.4 \times 10^{-4} \text{erg} \cdot \text{s}^{-1} (4\pi f) F_{\nu} (\text{mJy}) d^2 (\text{kpc}) \times \Delta \nu P_{\text{GJ}} B_{12}^{-1} \xi^{-1} l_6^{-2} s_8^{-1}. \tag{6}
\]

Any mechanism with \( P_{\text{sing}} > P_{\text{sing,c}} \) could meet the energy budget constraint. Note \( l = 10^6 \text{cm} l_6 \) and \( s = 10^6 \text{cm} s_6 \) are adopted as the typical linear size of the emission region which contributes to the pulsar luminosity (Manchester & Taylor 1977; Lesch et al. 1998). This is a little bit arbitrary, and \( P_{\text{sing,c}} \) is quite sensitive to this parameter. If \( l_6 \) is finally determined to be much less than 1, then \( P_{\text{sing,c}} \) should be raised. Note that the typical value of \( F_{\nu} (\text{mJy}) d^2 (\text{kpc}) \) is larger than 1. This also raises \( P_{\text{sing,c}} \). However, two effects, namely the beaming effect \((4\pi f)\) and the enhancement of another factor \( \xi \) could compensate the enhancement of \( P_{\text{sing,c}} \). Thus \( \sim 10^{-4} - 10^{-3} \text{erg} \cdot \text{s}^{-1} \) could be a fair critical value of the emission power of the particles.

Such a critical value is too high for a less efficient mechanism (e.g. curvature radiation, see next section), but is unmountable in principle. Using the constraint that the total emission energy over the emitting length is less than the kinetic energy of the particle, i.e., \( P_{\text{sing,c}} \cdot s/c < (\gamma - 1) mc^2 \), we obtain a very loose constraint as \( \gamma - 1 > P_{\text{sing,c}} \cdot s/mc^2 > 5.7 \times 10^{-3} (4\pi f) F_{\nu} (\text{mJy}) d^2 (\text{kpc}) \Delta \nu P_{12}^{-1} \xi^{-1} l_6^{-2} \).

Next we’ll examine the concrete direct emission mechanisms to see whether the high power defined by [6] is achievable.

3. CURVATURE RADIATION (CR) AND INVERSE COMPTON SCATTERING (ICS)

The curvature radiation (CR) has long been regarded as a promising candidate to explain pulsar radio emission (e.g. Sturrock 1971, Ruderman & Sutherland 1975), since its characteristic frequency \( \nu_{\text{CR}} = (3/4\pi) (\gamma^3/\rho) \simeq 7.2 \times 10^9 \text{Hz} \gamma_3^3 \rho_8^{-1} \) is just well within the observed emission band of pulsars. However, the emission power of a single particle

\[
P_{\text{sing,CR}} = \frac{2}{3} \gamma^4 c^5 \rho^2 \simeq 4.6 \times 10^{-13} \text{erg} \cdot \text{s}^{-1} \gamma_3^3 \rho_8^{-2} \tag{7}
\]

is much lower than \( P_{\text{sing,c}} \) in eq.[6]. Thus incoherent CR is definitely ruled out as the candidate for pulsar radio emission (see also Lesch et al. 1998). This might be the primary motivation of introducing “bunching” coherent mechanisms in the early studies. It is worth noting here that even the coherent CR mechanism has been criticized from the observational points of views (Lesch et al. 1998). Another objection is, when taking into account the energy loss of the secondaries, the required Lorentz factor of particles in the CR mechanism may lie above the “Lorentz platform”, which makes it impossible to explain the low frequency emission from some pulsars (Zhang et al. 1997b).

Another direct emission model is the inverse Compton scattering model proposed by Qiao (1988) and QL98. In such a model, a low frequency electro-magnetic wave is assumed to exist in the pulsar magnetosphere near the polar cap region, which is generated either by the breaking down of the vacuum polar gap (Ruderman & Sutherland 1975; Zhang et al. 1997a,b) or other sorts of short-time oscillations or micro-instabilities (Björnsson 1996). Such a wave is assumed to be inverse Compton scattered to the radio frequency we observe. The typical emission frequency for the ICS process reads \( \nu_{\text{ICS}} = 2\gamma^2 \nu_{\text{cap}} (1 - \beta \cos \theta_i) \), where \( \nu_{\text{gap}} \sim c/h \) (is the gap height, typically \( 10^4 \text{cm} \)), \( \theta_i \) is the incident angle of the scattering, and \( \cos \theta_i = [2 \cos \theta + (R/r)(1 - 3 \cos^2 \theta)] / [(1 + 3 \cos^2 \theta)(1 - 2(R/r) \cos \theta + (R/r)^2)]^{1/2} \) (QL98). Near the polar cap region, the typical value for \( (1 - \beta \cos \theta_i) \) is \( \sim 0.005 \), thus the
typical frequency of the ICS mechanism is $\nu_{\text{ICS}} \simeq 3.0 \times 10^9 \text{Hz}$, which is the typical frequency of pulsar radio emission. The emission power of a single particle due to ICS is $P_{\text{sing,ICS}} \simeq \gamma^2 \sigma_c U_{\text{ph}}$, where $\sigma$ is the magnetized ICS cross section across frequency waves (see details in QL98). With the Thomson cross section $\sigma_{\text{th}} = 6.65 \times 10^{-25} \text{cm}^2$, we finally obtain

$$P_{\text{sing,ICS}} \simeq 5.6 \times 10^{-2}\text{erg} \cdot \text{s}^{-1} B_{12}^2 P_{0.1}^{-2} \nu_3^2.$$  \hspace{1cm} (8)

This is higher than the critical value in eq.[6]. Note both in eq.[6] and [8], the typical $P$ is adopted as 0.1s, which is the case for the majority of the pulsars. If $P$ is typically adopted as 1s, then eq.[8] is less than [6], which means that energy budget constraint still rules out the incoherent ICS process. This is consistent with the conclusions in QL98 (their Appendix C). Nevertheless, we have shown that the ICS mechanism can marginally meet the energy budget requirement.

4. CONCLUSIONS

In this Letter, we have re-investigated the concepts of coherent emission and posed two constraints on any incoherent emission mechanism in pulsar magnetospheres. The energy budget constraint [2b] could be released by introducing an efficient radiation mechanism (e.g. ICS). If the optical-thin constraint [2a] is also released, certain coherent mechanisms such as “bunching” or “maser amplification”, are not obligatory any more. This in principle brings the possibility to interpret the high luminosities of pulsar in terms of incoherent emission mechanism. Though lack of an executable mechanism to release the optical-thin constraint without invoking any coherent mechanism, we suppose that there might be some possible way out after presenting some criticisms on the present studies. If one could find a regime where $\tau < 1$ [2a] is satisfied without invoking maser mechanism ($\tau < 0$, a coherent mechanism), then coherence is no longer essential to account for pulsar radio emission provided an efficient enough mechanism.

We are not insisting here that the emission is definitely incoherent though. Besides the motivations to release the constraints [2a,b], coherence is also helpful to explain some other features of observations. For example, certain extent of coherence is required to account for the polarization features in the ICS model (e.g. Liu, Qiao, & Xu 1998). Nevertheless, if the emission power of a single particle is high enough (e.g. ICS mechanism), and if the pulsar magnetospheres are really transparent, the general criticisms (M78; M92a,b) on the bunching coherent mechanisms are greatly weakened, since a more efficient mechanism (e.g. ICS) only need a much weaker degree of coherence, so that an instant or local bunching mechanism has been already adequate to account for the high luminosities. Even if the optical-thin constraint can not be released unless certain coherent mechanism is incorporated, a high efficiency mechanism is also helpful to meet the requirement of the “highest brightness temperature” limit discussed in M92a.

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