

# On the simultaneous generation of radio and soft X-ray emission by AXP 4U 0142+61

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## Abstract

In the present paper we study the possibility of a simultaneous generation of radio waves and soft X-rays by means of the quasi-linear diffusion (QLD) in the anomalous pulsar AXP 4U 0142+61. Considering the magnetosphere composed of the so-called beam component and the plasma component respectively, we argue that the frozen-in condition will inevitably lead to the generation of the unstable cyclotron waves. These waves, via the QLD, will in turn influence the particle distribution function, leading to certain values of the pitch angles, thus to an efficient synchrotron mechanism, producing soft X-ray photons. We show that for physically reasonable parameters of magnetospheric plasmas, the QLD can provide generation of radio waves in the following interval 40 MHz-111 MHz connected to soft X-rays for the domain 0.3keV-1.4keV.

**Keywords:** *pulsars: individual: AXP 4U 0142+61 – stars: magnetars – radiation mechanisms: non-thermal – plasmas.*

## 1. Introduction

Anomalous X-ray pulsars (AXPs) (young isolated neutron stars) since their discovery (Fahlman & Gregory, 1981, e.g. Mazets et al., 1971) deserve a great attention despite a few number of known AXPs (Kaspi, 2007). These objects are intensively studied last several years, but their nature still remains unknown. One of the interesting features of AXPs is their long period of rotation, which in turn leads to very strong magnetic fields exceeding the so-called Schwinger limit,  $B_{cr} \approx 4.41 \times 10^{13}$  G. Therefore, they are called magnetars. AXPs exhibit strong X-ray fluxes and a corresponding luminosity exceeds the spin-down luminosity by many orders of magnitude. On the other hand, despite some predictions, that magnetars must be dark in the radio band (e.g. Baring & Harding, 1998), Camilo et al. (2006) and Malofeev et al. (2010) reported the detection of radio pulsations from magnetar-type neutron stars. In particular, Camilo et al. (2006) observed the position of the anomalous pulsar XTE J1810 - 197 at frequencies from  $\nu = 1.4$  GHz to  $\nu = 49$  GHz. It was shown that XTE J1810 - 197 emits bright, narrow, highly linearly polarized radio pulses. Malofeev et al. (2010), based on two high-sensitivity radio telescopes of the Pushchino Radio Astronomy Observatory - the Large Phased Array and the DKR-1000, have reported the detection of weak radio pulsed emission from the X-ray pulsar AXP 4U 0142+61 at two low frequencies, 40 MHz and 111 MHz. It is worth noting that this pulsar was monitored by the Westerbork Synthesis Radio Telescope at a frequency 1380 MHz. The observations did not detect a source of radio emission (with 1380 MHz) at the location of AXP 4U 0142+61.

In the present paper we focus on the anomalous X-ray pulsar 4U 0142+61, which exhibits radiation from the soft- to hard- X-rays, (e.g. den Hartog et al., 2006, Enoto et al., 2011, Góhler et al., 2005). The aim of this work is to study the possibility of a simultaneous generation of soft X-rays and radio waves stimulated by the quasi-linear diffusion (QLD). For explaining the radiation in the soft X-rays, we account for the synchrotron emission process. But, since in the magnetospheres of magnetars. magnetic fields are very strong, the corresponding energy losses are efficient and for studying the

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synchrotron radiation one has to take into account a certain mechanism balancing the dissipative factors. This in turn leads to the one dimensional distribution function of particles and as a result the synchrotron mechanism completely vanishes. In this paper we rely on the pulsar emission model developed by [Lominadze et al. \(1979\)](#), [Machabeli & Usov \(1979\)](#). According to this approach, in the pulsar magnetospheres the cyclotron instability appears ([Kazbegi et al., 1992](#)), which during the quasi-linear stage, causes a diffusion of particles along and across the magnetic field lines, leading to the required balance.

This mechanism was applied to magnetars, pulsars and active galactic nuclei in a series of papers: ([Chkheidze et al., 2010](#), [Machabeli & Osmanov, 2009, 2010](#), [Malov & Machbeli, 2001](#), [Osmanov, 2014](#), [Osmanov & Machabeli, 2010](#), [Osmanov, 2010a,b](#)). One of the interesting consequences of the QLD is the fact that it provides a simultaneous generation of waves in two different emission bands: relatively low energy- and high energy- domains. In particular, the high energy radiation appears by means of the feedback of the cyclotron waves on relativistic particles due to the diffusion, and as a result, the pitch angles are arranged according to the aforementioned balance. Therefore, during the QLD, the physical system will be characterized by two radiation regimes: (a) the high energy synchrotron mechanism and (b) a low energy emission process provided by the cyclotron waves. In this context the recent observations performed by the MAGIC Cherenkov telescope deserve a great interest. In particular, [Aliu et al. \(2008\)](#) reported about the discovery of the very high energy (VHE) pulsed emission ( $> 25$  GeV) from the Crab pulsar and it has been shown that the VHE signals are coincident with optical signals in a phase. For explaining the origin of the coincidence, [Machabeli & Osmanov \(2009\)](#) have considered the mechanism of the QLD applying it to the plasmas in the magnetosphere of the Crab pulsar on the light cylinder (a hypothetical area where the linear velocity of rigid rotation exactly equals the speed of light) lengthscales. We have found that the QLD provides the simultaneous generation of emission in different frequency bands. In the later studies ([Chkheidze et al., 2010](#), [Machabeli & Osmanov, 2010](#)) the same problem was examined in more detail.

In the present paper we consider the anomalous pulsar 4U 0142+61 to investigate the role of the QLD in generation of the detected soft  $X$ -rays and radio waves respectively. The paper is organized as follows: In Section 2 we introduce the mechanism of the QLD, in Sect. 3 we apply the method to AXP 4U 0142+61 and obtain results, and in Sect. 4 we summarize them.

## 2. Main consideration

We assume that the pulsar's magnetosphere is composed of the so-called primary beam with the Lorentz factor,  $\gamma_b$  and the bulk component with the Lorentz factor,  $\gamma_p$  ([Chkheidze et al., 2010](#), [Machabeli & Osmanov, 2009, 2010](#)). By [Kazbegi et al. \(1992\)](#) it was shown that in the pulsar magnetospheric plasmas, which satisfy the frozen-in condition, the anomalous Doppler effect induces resonance unstable cyclotron waves

$$\omega - k_{\parallel} c - k_x u_x - \frac{\omega_B}{\gamma_b} = 0 \quad (1)$$

with the corresponding frequency ([Malov & Machbeli, 2001](#))

$$\nu \approx \frac{\omega_B}{2\pi\delta\gamma_b}, \quad \delta = \frac{\omega_p^2}{4\omega_B^2\gamma_p^3}, \quad (2)$$

where  $k_{\parallel}$  is the longitudinal (along the magnetic field lines) component of the wave vector,  $u_x \approx c^2\gamma_b/(\rho\omega_B)$  is the so-called curvature drift velocity,  $c$  is the speed of light,  $\rho$  is the magnetic fields' curvature radius,  $k_x$  is the wave vector's component along the drift,  $\omega_B \equiv eB/mc$  is the cyclotron frequency,  $B \approx 2.35 \times 10^{14} R_{st}^3/R^3 \text{G}$  is the magnetic induction close to the star's surface,  $R_{st} \approx 10^6 \text{cm}$  is the pulsar's radius,  $R$  is the distance from the pulsar's center,  $e$  and  $m$  are the electron's charge and the rest mass respectively,  $\omega_p \equiv \sqrt{4\pi n_p e^2/m}$  is the plasma frequency and  $n_p$  is the plasma number density.

For studying the development of the QLD, one should note that two major forces control dissipation. When particles emit in the synchrotron regime, they undergo the radiative reaction force  $\mathbf{F}$ ,

having the following components (Landau & Lifshitz, 1971):

$$F_{\perp} = -\alpha_s \frac{p_{\perp}}{p_{\parallel}} \left( 1 + \frac{p_{\perp}^2}{m^2 c^2} \right), F_{\parallel} = -\frac{\alpha_s}{m^2 c^2} p_{\perp}^2, \quad (3)$$

where  $\alpha_s = 2e^2 \omega_B^2 / 3c^2$  and  $p_{\perp}$  and  $p_{\parallel}$  are the transversal (perpendicular to the magnetic field lines) and longitudinal (along the magnetic field lines) components of the momentum respectively.

In nonuniform magnetic field, electrons also experience a force  $\mathbf{G}$ , that is responsible for conservation of the adiabatic invariant,  $I = 3cp_{\perp}^2 / 2eB$ . The corresponding components of  $\mathbf{G}$  are given by (Landau & Lifshitz, 1971):

$$G_{\perp} = -\frac{cp_{\perp}}{\rho}, \quad G_{\parallel} = \frac{cp_{\perp}^2}{\rho p_{\parallel}}. \quad (4)$$

The wave excitation leads to a redistribution process of the particles via the QLD, which is described by the following kinetic equation (Machabeli & Usov, 1979, Malov & Machabeli, 2002)

$$\begin{aligned} \frac{\partial f}{\partial t} + \frac{1}{p_{\perp}} \frac{\partial}{\partial p_{\perp}} (p_{\perp} [F_{\perp} + G_{\perp}] f) = \\ = \frac{1}{p_{\perp}} \frac{\partial}{\partial p_{\perp}} \left( p_{\perp} D_{\perp, \perp} \frac{\partial f}{\partial p_{\perp}} \right), \end{aligned} \quad (5)$$

where  $f$  is the distribution function of the zeroth order,  $D_{\perp, \perp} = D\delta|E_k|^2$ , is the diffusion coefficient,  $|E_k|^2$ , is the energy density per unit of wavelength and  $D = e^2 / 8c$  (Chkheidze et al., 2010). For estimating  $|E_k|^2$ , it is natural to assume that half of the plasma energy density,  $mc^2 n_b \gamma_b / 2$  converts to the energy density of the waves  $|E_k|^2 k$ , then for  $|E_k|^2$  we obtain

$$|E_k|^2 = \frac{mc^3 n_b \gamma_b}{4\pi\nu}, \quad (6)$$

where

$$n_b = \frac{B}{Pce}, \quad (7)$$

is the number density of the beam and  $P \approx 8.7$ s is the rotation period of the pulsar.

By taking into account the relations  $\psi \equiv p_{\perp} / p_{\parallel}$ ,  $p_{\parallel} = mc\gamma_b$ , one can show from Eqs. (3,4) that

$$\frac{F_{\perp}}{G_{\perp}} \approx 2.7 \times 10^{-6} \times \left( \frac{B}{10^3 G} \right)^2 \times \left( \frac{\gamma_b}{10^7} \right) \times \left( \frac{\psi}{10^{-5} rad} \right)^2, \quad (8)$$

where  $B$  is normalized to the value of the magnetic field in the magnetosphere on the lengthscales,  $\sim 10^{10}$ cm. We see from this ratio that for physically reasonable parameters, one can neglect the transversal component of the radiation reaction force. Therefore, Eq. (5) reduces to

$$\begin{aligned} \frac{\partial f}{\partial t} + \frac{1}{p_{\perp}} \frac{\partial}{\partial p_{\perp}} (p_{\perp} G_{\perp} f) = \\ = \frac{1}{p_{\perp}} \frac{\partial}{\partial p_{\perp}} \left( p_{\perp} D_{\perp, \perp} \frac{\partial f}{\partial p_{\perp}} \right). \end{aligned} \quad (9)$$

As it is clear from Eq. (9), two major factors compete in this "game". On the one hand, the force responsible for conservation of the adiabatic invariant attempts to decrease the transversal momentum (thus the pitch angle), whereas the diffusion process, by means of the feedback of the cyclotron waves, attempts to increase the transversal momentum. Dynamically this process saturates when the aforementioned factors balance each other. Therefore, it is natural to study the stationary regime,  $\partial f / \partial t = 0$  and examine a saturated state of the distribution function. After imposing the condition  $\partial f / \partial t = 0$  on Eq. (9) one can straightforwardly solve it

$$f(p_{\perp}) = C \exp \left( \int \frac{G_{\perp}}{D_{\perp, \perp}} dp_{\perp} \right) = C e^{-\left( \frac{p_{\perp}}{p_{\perp 0}} \right)^2}, \quad (10)$$

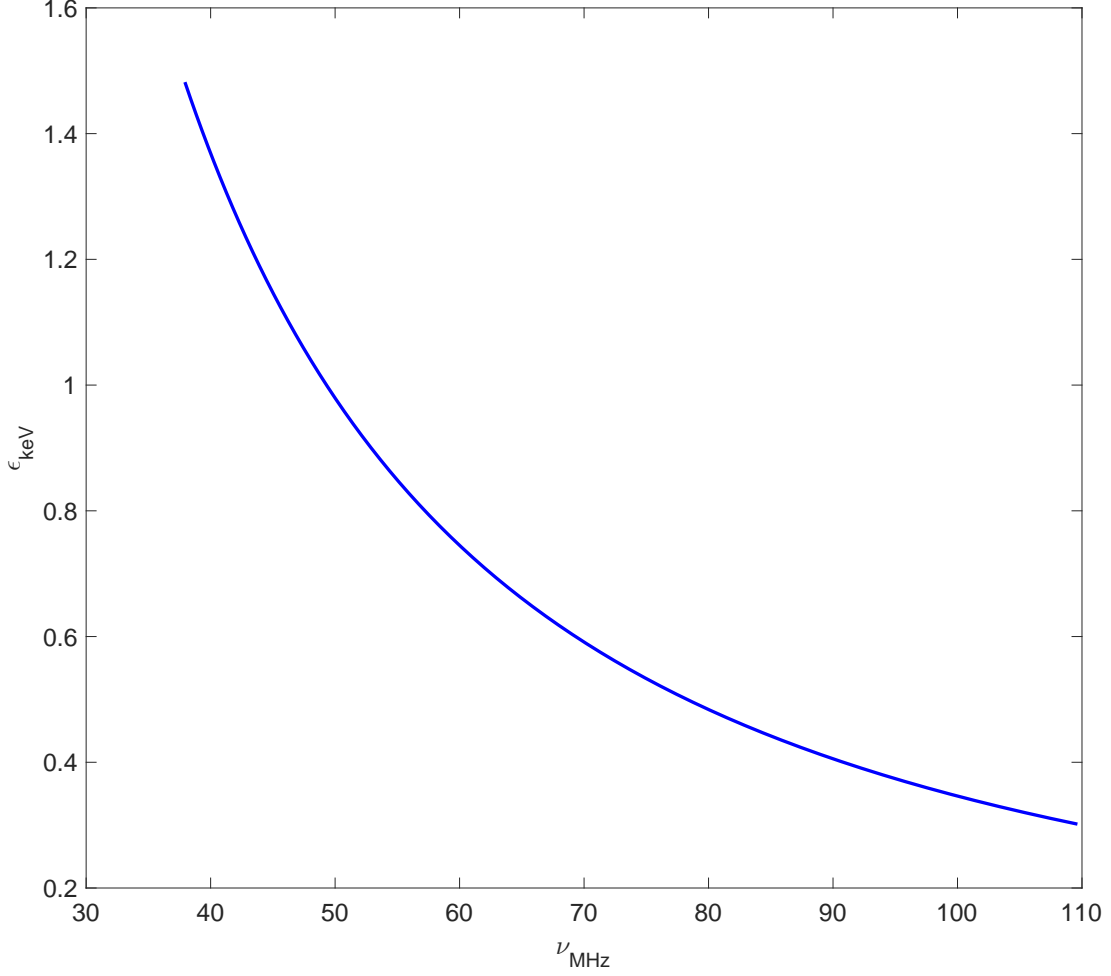


Figure 1. Behaviour of  $\epsilon_{keV}$  with respect to  $\nu_{MHz}$ . The set of parameters is:  $P \approx 8.7$ ,  $\gamma_p = 2.77$ ,  $B_{st} \approx 1.3 \times 10^{14} \text{G}$ ,  $R_{st} \approx 10^6 \text{cm}$ ,  $R = 4.8 \times 10^9 \text{cm}$ .

where  $C = const$  and

$$p_{\perp 0} \equiv \left( \frac{2\rho D_{\perp, \perp}}{c} \right)^{1/2}. \quad (11)$$

Since  $f$  is a continuous function of the transversal momentum, it is natural to examine an average value of it and estimate the corresponding mean value of the pitch angle,  $\bar{\psi} \equiv \bar{p}_{\perp 0}/p_{\parallel}$ ,

$$\bar{\psi} = \frac{1}{p_{\parallel}} \frac{\int_0^{\infty} p_{\perp} f(p_{\perp}) dp_{\perp}}{\int_0^{\infty} f(p_{\perp}) dp_{\perp}} \approx \frac{1}{\sqrt{\pi}} \frac{p_{\perp 0}}{p_{\parallel}}. \quad (12)$$

As the investigation shows, the QLD leads to a certain distribution of particles with the pitch angles, which will inevitably result in the synchrotron radiation mechanism with the following energy of emitted photons (e.g. Rybicki & Lightman, 1979)

$$\epsilon_{eV} \approx 1.2 \times 10^{-8} B \gamma_b^2 \sin \bar{\psi}. \quad (13)$$

### 3. Results

In this section we will apply the mechanism of the quasi-linear diffusion to the anomalous pulsar 4U 0142+61 for studying the possibility of simultaneous generation of radio waves and soft X-rays. In the  
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framework of the proposed model, the QLD is provided by the feedback of the cyclotron waves. Let us consider mildly relativistic particles of the plasma component with  $\gamma_p = 3$  and the beam component with  $\gamma_b = 10^7$ . Then, by taking into account that the energy is uniformly distributed,  $n_b\gamma_b \approx n_p\gamma_p$ , one can reduce Eq.(2)

$$\nu \approx 1.9 \times \left(\frac{\gamma_p}{3}\right)^4 \times \left(\frac{\gamma_b}{10^7}\right)^{-2} \times \left(\frac{R}{10^{10}cm}\right)^{-6} MHz. \quad (14)$$

As we see from this expression, the cyclotron frequency is very sensitive to a location in the magnetosphere. One can straightforwardly show that considering the following interval of the beam Lorentz factors  $(1 - 2) \times 10^7$  the best fit to observations (40MeV, 111MeV) is achieved by the parameters,  $\gamma_p \sim 2.77$ ,  $R \sim 4.8 \times 10^9$ cm. Despite the mentioned fact that these are resonance cyclotron waves, we see that the corresponding frequency interval is relatively wide. The reason is following: the resonance happens for given values of the Lorentz factors - thus for a certain value of it, there is a certain value of the radiation frequency. But relativistic particles are distributed by their kinetic energy, which lies in a broad interval. Therefore, in exciting waves all resonance particles (with broad energy spectra) participate and the resulting frequencies will have a relatively broad interval as well.

As a next step we would like to estimate how efficient is the mentioned instability. Kazbegi et al. (1992) have shown that for  $\gamma_b/(2\rho\omega_B) \ll \delta$  (which is the case) the increment characterizing amplification of the cyclotron waves is given by

$$\Gamma = \frac{\omega_b^2}{2\nu\gamma_p}, \quad (15)$$

where  $\omega_b \equiv \sqrt{4\pi n_b e^2/m}$  is the plasma frequency corresponding to the beam component. One can show that for the aforementioned parameters, the value of the growth rate lies in the following interval  $\sim 10^3 - 10^4 s^{-1}$ . Therefore, the corresponding timescale,  $\tau \sim 1/\Gamma$ , is of the order of  $\sim 10^{-4} - 10^{-3} s$ . On the other hand, we have seen that the best fit to observations is achieved for the waves excited in the location,  $R \sim 5.9 \times 10^9$ cm. This means that plasmas stay inside the magnetosphere for relatively long time. In particular, the escape timescale,  $t_{esc} \sim (R_{lc} - R)/c$  ( $R_{lc} = cP/(2\pi)$  is the light cylinder radius) is of the order of  $\sim 1s$ . As we see, the instability timescale is by many orders of magnitude less than the escape timescale, which means that the process is extremely efficient and physically feasible.

We have already explained that the cyclotron waves will influence the particle distribution via diffusion (feedback mechanism) leading to certain pitch angles (see Eqs. (12,13)). In Fig. 1 we show the dependence of synchrotron photon energy on the radio frequency. The set of parameters is:  $P \approx 8.7s$ ,  $\gamma_p = 2.77$ ,  $B_{st} \approx 1.3 \times 10^{14}G$ ,  $R_{st} \approx 10^6$ cm,  $R = 4.8 \times 10^9$ cm. It is clear from the plot that  $\epsilon_{keV}$  is a continuously decreasing function of radio frequencies. This is direct consequence of Eqs. (2,6,11,12,13). In particular, according to Eq. (13) the photon energy behaves as to be  $\epsilon_{eV} \sim \gamma_b \bar{\psi}$ , on the other hand, by taking into account the relation  $D_{\perp,\perp} = D\delta|E_k|^2$ , one can see from Eqs. (6,11,12) that  $\bar{\psi} \sim \gamma_b$ , which by combining with Eq. (13) leads to the following dependence  $\epsilon_{eV} \sim \gamma_b^3$ . Therefore, more energetic particles produce more energetic synchrotron photons, but since the cyclotron frequency is a decreasing function of  $\gamma_b$  (see Eq. (14)), lower radio frequencies correspond to higher X-ray photon energies.

As it is clear from the plot, the relativistic electrons with Lorentz factors  $(1 - 1.7) \times 10^7$ , can lead to a simultaneous generation of radio waves (from 40 MHz to 111 MHz) and soft X-rays (from 0.3 - 1.4 keV) respectively. According to the proposed model, emission mechanisms are produced by plasmas inside the magnetosphere of the anomalous pulsar 4U 0142+61, relatively far as from the neutron star's surface, as from the light cylinder area,  $R \sim 4.8 \times 10^9$ cm.

## 4. Summary

The main aspects of the present work can be summarized as follows:

- 1) In this paper we examined the role of the quasi-linear diffusion in producing soft X-rays and radio emission in the magnetosphere of the anomalous pulsar 4U 0142+61.

- 2) Considering the anomalous Doppler effect, which leads to the unstable cyclotron waves, we have studied the feedback of these waves on a distribution of relativistic particles. Solving the equation governing the QLD, the corresponding expression of the average value of the pitch angle is derived and analyzed for physically reasonable parameters. It has been found that the higher the the synchrotron photon energy, the lower the radio frequency.
- 3) We have shown that the quasi-linear diffusion might provide a simultaneous generation of radio emission (40MHz-111MHz) and soft  $X$ -rays (0.3keV-1.4keV) in plasmas located on the distance  $4.8 \times 10^9$ cm from the pulsar's center for appropriate parameters  $\gamma_p = 2.77$ ,  $\gamma_b = (1 - 1.7) \times 10^7$ .

The present investigation shows that the QLD is a mechanism that can explain a simultaneous generation of the observationally evident radio waves (Malofeev et al., 2010) and soft  $X$ -rays (Göhler et al., 2005). The aim of the present paper was to examine only one part of the problem, although a complete study requires to investigate the spectral pattern of emission as well. In the standard theory of the synchrotron emission it is assumed that due to the chaotic character of the magnetic field lines (Bekefi & Barrett, 1977, Ginzburg, 1981), the pitch angles lie in a broad interval (from 0 to  $\pi/2$ ). In our model the distribution function of particles is strongly influenced by the process of the QLD and as a result the pitch angles are restricted by the balance of dissipative and diffusive factors. This will inevitably lead to a spectral pattern, different from that of Bekefi & Barrett (1977), Ginzburg (1981). Therefore, we will investigate this problem in future studies.

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