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On the Circular Polarization of Repeating Fast Radio Bursts

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Abstract

Fast spinning (e.g., sub-second) neutron star with ultra-strong magnetic fields (or so-called magnetar) is one of the promising origins of repeating fast radio bursts (FRBs). Here we discuss circularly polarized emissions produced by propagation effects in the magnetosphere of fast spinning magnetars. We argue that the polarization-limiting region is well beyond the light cylinder, suggesting that wave mode coupling effects are unlikely to produce strong circular polarization for fast spinning magnetars. Cyclotron absorption could be significant if the secondary plasma density is high. However, high degrees of circular polarization can only be produced with large asymmetries in electrons and positrons. We draw attention to the non-detection of circular polarization in current observations of known repeating FRBs. We suggest that the circular polarization of FRBs could provide key information on their origins and help distinguish different radiation mechanisms.

Unified Astronomy Thesaurus concepts: Radio transient sources (2008); Magnetars (992); Neutron stars (1108); Radio bursts (1339); Non-thermal radiation sources (1119)

1. Introduction

Fast radio bursts (FRBs) are bright millisecond-duration radio transients first discovered by Lorimer et al. (2007). Their cosmological origin and energetic nature make them ideal tools to probe a range of astrophysical and fundamental physics (e.g., Ravi et al. 2016; Prochaska et al. 2019; Macquart et al. 2020). Our knowledge of the progenitors of FRBs and the radiation mechanism is limited and whether repeating and non-repeating FRBs share the same origin is still an open question (see Zhang 2020, for a review). Recently, Pleunis et al. (2021) presented a synthesis of morphology of 18 repeating FRBs and 474 non-repeating FRBs. They showed that bursts from repeating FRBs, on average, have larger widths and are narrower in bandwidth. Comparisons of FRB luminosity functions with predictions based on event rate densities of various models also show that it is hard to explain both repeating and non-repeating FRBs with the same origin (e.g., Luo et al. 2020a). Precise localization of repeating and non-repeating FRBs (e.g., Chatterjee et al. 2017; Bannister et al. 2019; Ravi et al. 2019; Marcote et al. 2020; Fong et al. 2021; Ravi et al. 2021; Kirsten et al. 2021b) showed that the properties of FRB host galaxies and local environments are diverse (e.g., Tendulkar et al. 2017; Bhandari et al. 2020; Heintz et al. 2020; Li & Zhang 2020).

Most theories of active repeating FRBs involve neutron stars as their central engine. They can be young/normal pulsars (e.g., Connor et al. 2016; Cordes & Wasserman 2016; Yang & Zhang 2018; Wang et al. 2019, 2020b; Yang et al. 2020), or pulsars with ultra-strong magnetic fields/magnetars (e.g., Dai et al. 2016; Katz 2016; Beloborodov 2017), or normal pulsars with external (e.g., Zhang 2017; Mottez et al. 2020) or internal (e.g., Wang et al. 2018) interactions. Pulsars with short spin periods and ultra-strong magnetic fields have drawn much attention since they are likely young and store a large amount of toroidal magnetic energy inside the star, which could explain their active bursting activities (e.g., Lu et al. 2020; Margalit et al. 2020). It has been proposed that rare, extreme explosions such as long gamma-ray bursts (Zhang & Mészáros 2001; Metzger et al. 2011), superluminous supernovae (e.g., Murase et al. 2016; Metzger et al. 2017), or neutron star mergers (e.g., Margalit et al. 2019; Jiang et al. 2020; Wang et al. 2020a) could produce such fast spinning pulsars with ultra-strong magnetic fields. Theories involve magnetars are supported by the recent detection of a FRB (FRB 200428) from the well-known Galactic magnetar SGR 1935+2154 (CHIME/FRB Collaboration et al. 2020; Bochenek et al. 2020). Magnetars as the origin of repeating FRBs were likely born with a faster initial spin and more toroidal magnetic energy inside the star, and are therefore more active compared with Galactic magnetars (e.g., Katz 2020; Lin et al. 2020; Lu et al. 2020; Margalit et al. 2020).

In addition to studies of the temporal and frequency structures of FRBs, the radio polarization properties of FRBs have been presented in a number of papers (e.g., Masui et al. 2015; Petroff et al. 2015; Caleb et al. 2018; Michilli et al. 2018; Day et al. 2020; Fonseca et al. 2020; Luo et al. 2020b; Nimmo et al. 2021). These observations and studies of radiation mechanism (e.g., Cordes & Wasserman 2016; Lu et al. 2019) have suggested that polarization properties might provide crucial information on the emission mechanism of FRBs. Propagation effects in the potentially dense and relativistic magneto-ionic environments of FRBs, such as Faraday

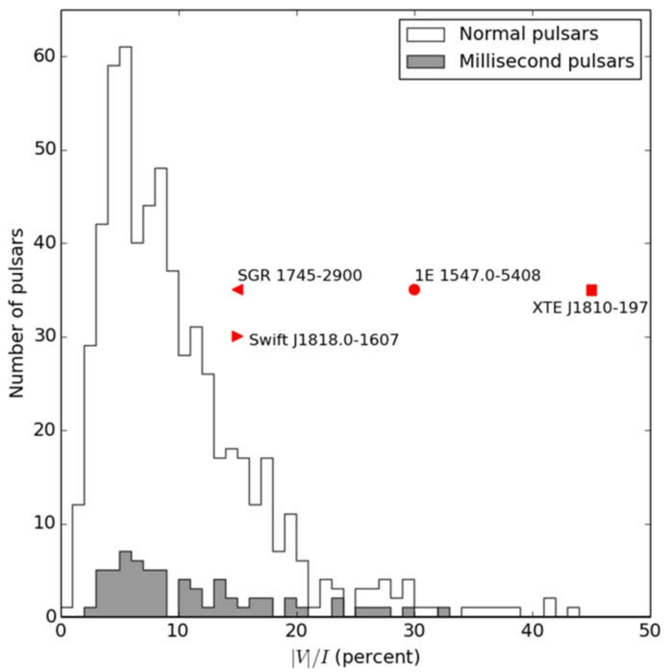

Figure 1. Histograms of fractional circular polarization ($|V|/I$) of normal pulsars (black line) and millisecond pulsars (filled region) at ∼1.4 GHz. Red points represent the fractional circular polarization of four radio-loud magnetars. We note that the circular polarization of magnetars often shows large variations, and the values shown here represent the high end of their fractional circular polarization.

conversion, have also been investigated. Vedantham & Ravi (2019) used the non-detection of Faraday conversion in FRB 121102 to constrain FRB progenitor models and the magnetic field in the cold confining medium. Gruzinov & Levin (2019) provided qualitative predictions for the circular polarization of FRBs produced by Faraday conversion and their narrow-band properties at low frequencies.

In this paper, we investigate the origin of circular polarization of fast spinning magnetars and discuss its implication on repeating FRBs. We focus on wave mode coupling and cyclotron absorption effects and argue that it is challenging to produce high degrees of circular polarization for fast spinning magnetars through propagation effects. Future studies (both observational and theoretical) of circular polarization of a large sample of repeating FRBs might reveal key information on their origins and radiation mechanisms. In Section 2, we will discuss observational properties of circular polarization of repeating and non-repeating FRBs. In Sections 3 and 4, the propagation effects of the fast spinning magnetar model will be discussed. A discussion and our conclusions will be given in Section 5.

2. Circular Polarization of Radio Pulsars and FRBs

Compared with other radio sources (e.g., active galactic nucleus), radio pulsars as a population show significantly stronger circular polarization. Figure 1 shows histograms of fractional circular polarization ($|V|/I$) of 600 normal pulsars (Johnston & Kerr 2018) and 63 ms pulsars at ∼1.4 GHz (Dai et al. 2015; Gentile et al. 2018; Wahl et al. 2021). We can see that the majority of this sample of pulsars show a fractional circular polarization of ∼5%–20%. More relevant to our discussion here is radio-loud magnetars. In Figure 1, red points show published fractional circular polarization of four radio-loud magnetars[11] (e.g., Camilo et al. 2008; Eatough et al. 2013; Dai et al. 2019; Lower et al. 2020). Although only five radio-loud magnetars are known so far, circular polarization stronger than the average of normal pulsars has been detected from all of them. After their outbursts, rapid changes in the strength and sign of circular polarization have been observed along with variations in linear polarization and position angles (e.g., Camilo et al. 2007; Levin et al. 2012; Dai et al. 2018, 2019). While several mechanisms have been proposed to explain observed circular polarization from normal radio pulsars (see discussion in Section 3), the case of the magnetar has not been explored in detail in the literature.

Polarized radio emission of FRBs shares many similarities with those of radio pulsars and magnetars. Variations in both linear and circular polarization across the pulse have been observed in non-repeating FRBs (e.g., Cho et al. 2020; Day et al. 2020), and polarized emission of several cases are dominated by linear polarization (e.g., Caleb et al. 2018; Cho et al. 2020). Strong circular polarization has been observed in a significant fraction of non-repeating FRBs (e.g., Masui et al. 2015; Petroff et al. 2015, 2017; Caleb et al. 2018; Cho et al. 2020; Day et al. 2020). In a case study of FRB 181112, Cho et al. (2020) suggested that the variation in the circular polarization across the profile provided evidence of radiation propagating through a relativistic plasma in the source region. They pointed out that such propagation effects could be common for non-repeating FRBs.

Some repeating FRBs also show high degrees of linear polarization. Diverse polarization angle swings observed in FRB 180301 is particularly reminiscent of the polarization properties of magnetars (Luo et al. 2020b). However, despite deep multiwavelength radio observations of FRBs 121102 (Scholz et al. 2016; Michilli et al. 2018; Hilmarsson et al. 2021), 171019 (Kumar et al. 2019), 180916.J015865 (Chawla et al. 2020; Nimmo et al. 2021), 180301 (Luo et al. 2020b), 20190711A (Kumar et al. 2021), and The Canadian Hydrogen Intensity Mapping Experiment (CHIME) repeating FRBs (CHIME/FRB Collaboration et al. 2019; Fonseca et al. 2020), no significant circular polarization has been detected. Although only two very active repeating FRBs (121102 and 180301) are known so far, the non-detection of circular polarization from any of their bursts is puzzling for models involving fast spinning magnetars. It would be intriguing to understand why fast spinning magnetars, assuming that they are the origin of repeating FRBs, are seemingly lack of strong circular polarization, while strong and highly variable circular polarization has been observed in all Galactic radio-loud magnetars.

3. Circular Polarization Produced by Propagation Effects

The origin of circular polarization from radio pulsars is a long-standing problem. Although many observational properties of pulsar circular polarization are not fully understood, it is generally believed that propagation effects in magnetospheric plasma play an essential role and could naturally produce circular polarization (e.g., Wang et al. 2010; Beskin &

[11] We note that high fractional circular polarization has also been observed in the Category III and IV profiles of PSR J1622-4950 (Levin et al. 2012), but exact numbers have not been published in the literature. For XTE J1810-197 and Swift J1818.0-1607, we used fractional circular polarization averaged across their wideband observations.

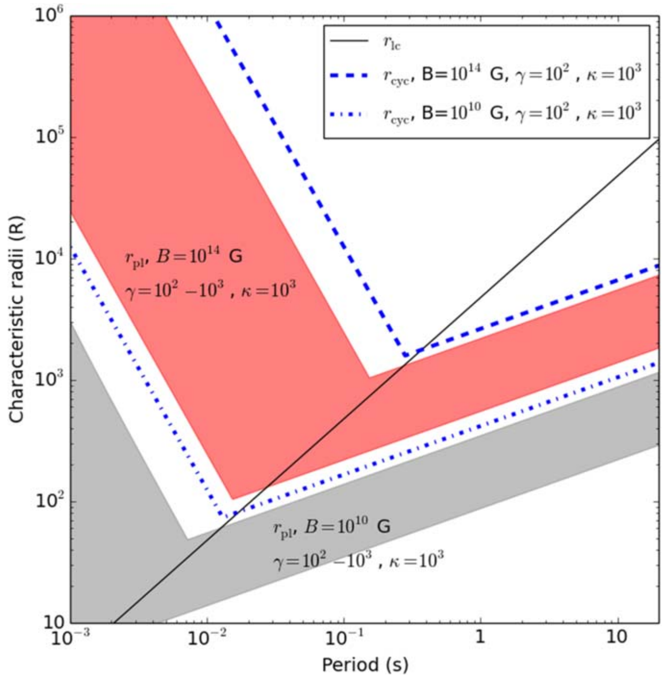

Figure 2. Polarization-limiting radius, r_{pl}, resonance radius, r_{cyc}, and light cylinder radius, r_{lc}, as a function of pulsar spin period. r_{pl} and r_{cyc} are estimated for a magnetic field strength of 10^{10}–10^{14} G. Shaded regions show r_{pl} with γ in the range of 10^2–10^3.

Philippov 2012). Propagation effects that have been widely discussed in the literature include the following:

1. Wave mode coupling (e.g., Cheng & Ruderman 1979; Stinebring 1982). In the vicinity of the emission origin, linearly polarized ordinary and extraordinary modes of normal waves propagate independently. In rotating magnetospheres with strong magnetic fields and relativistic plasma, the polarization plane of normal waves is tilted to the ambient magnetic line planes, which produces observable circular polarization. As the emission propagates, the plasma density decreases and eventually stops influencing the waves. This is where the polarization becomes fixed, and is characterized by the so-called polarization-limiting radius, r_{pl}. Studies of wave mode coupling and polarization transfer in relativistic plasma have been published in several papers (e.g., Barnard 1986).
2. Cyclotron absorption. Cyclotron absorption of radio emission within pulsar magnetospheres has been studied by Blandford & Scharlemann (1976), Luo & Melrose (2001), and Fussell et al. (2003). Cyclotron resonance occurs when the wave frequency in the electron/positron rest frame is close to the cyclotron frequency. When there is an asymmetry between electrons and positrons, the intensities of left- and right-handed waves are different after the cyclotron absorption, which results in circular polarization. In the inner magnetosphere, the Doppler shifted cyclotron frequency is much higher than the wave frequency. However, as waves propagate, the cyclotron frequency decreases and cyclotron absorption becomes significant when the cyclotron frequency is equal to the wave frequency. Such a condition occurs at the resonance radius, r_{cyc}.

Another effect that has been investigated in the literature is circularization of natural waves (e.g., von Hoensbroech et al. 1998; Petrova & Lyubarskii 2000; Wang et al. 2010; Beskin & Philippov 2012). Circular polarization is generated as natural waves propagating through pulsar magnetospheres along curved field lines. However, as shown by von Hoensbroech et al. (1998), for a strong magnetic field, circularization only happens when the wavevector is nearly aligned with the magnetic field (also see the discussion in Wang et al. 2010). For a relativistic plasma, the intersecting angle between the propagating beam and the magnetic field is Lorentz transformed (i.e., the angle increases), which suggests that natural waves are more likely to be highly linearly polarized (von Hoensbroech et al. 1998).

In this paper, we focus on wave mode coupling and cyclotron absorption effects for the special case of fast spinning magnetars. For normal radio pulsars (with a spin period of $\sim$1 s and a dipole magnetic field of $\sim 10^{12}$ G), Wang et al. (2010) carried out detailed studies of various propagation effects and concluded that the observed circular polarization is determined by the wave mode coupling, while cyclotron absorption only changes the total intensity. Wang et al. (2010) also showed that, for typical pulsar magnetosphere parameters, such as a Lorentz factor γ of $\sim$100 and a plasma density of $\eta \equiv N/N_{GJ} \sim 100$, characteristic radii of various propagation effects follow

$$r_{pl} < r_{cyc} \lesssim r_{lc}, \tag{1}$$

where $r_{lc} = c/\Omega$ is the radius of the light cylinder and Ω is the angular spin frequency. In the following section, we will show that r_{pl} and r_{cyc} are most likely to be much larger than r_{lc} for fast spinning magnetars, which will have important implications on the degree of circular polarization expected in the observed radio emission.

4. Propagation Effects for Fast Spinning Magnetars

Fast spinning (e.g., sub-second) neutron stars with ultra-strong magnetic fields (or so-called magnetars) have attracted much attention in order to understand the origin of FRBs, particularly for repeating FRBs (e.g., Lu et al. 2020). While ultra-strong magnetic fields and short spin periods can help explain repeating burst activities, they imply that pulsar magnetospheres are small (i.e., small r_{lc}) and regions where wave mode coupling and cyclotron absorption occur are far away from the star (i.e., large r_{pl} and r_{cyc}).

Here we have adopted the solutions of the magnetic field structure and evaluations of r_{pl} and r_{cyc} given by Barnard (1986). Outside the light cylinder, Barnard (1986) assumed that plasma flows in a nearly radial direction (the plasma density follows $\eta \propto r^{-2}$) and the magnetic field follows $B_r \approx B_r(r_{lc})(r_{lc}/r)^2$. While the structure of magnetic field and properties of plasma outside the light cylinder of fast spinning magnetars could be much more complex than this, Barnard (1986) provided a self-consistent solution and allows us to carry out an order-of-magnitude estimate. It is worth noting that most previous studies of the origin of circular polarization focused on propagation effects within the light cylinder of normal pulsars, and the case of fast spinning magnetars has not been discussed before.

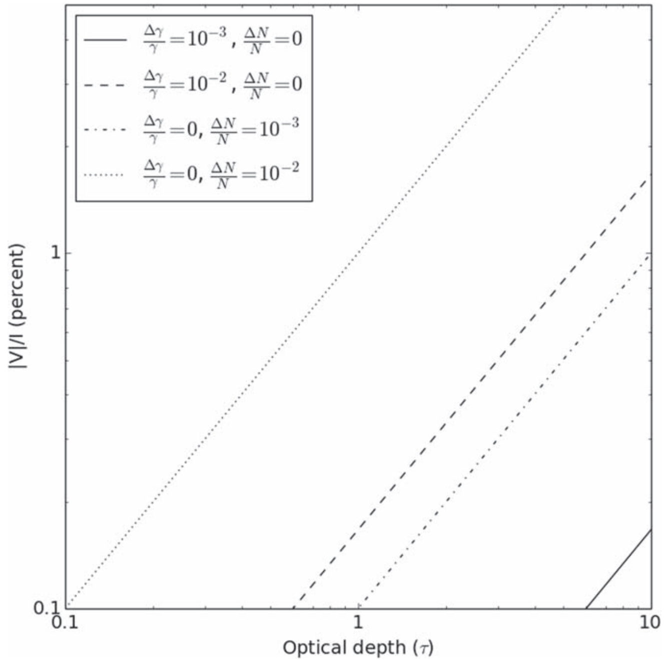

Figure 3. Degree of circular polarization as a function of the optical depth of cyclotron absorption. Different lines show how the degree of circular polarization changes with different levels of asymmetry in electrons and positrons.

Following Barnard (1986), we estimate the cyclotron absorption radius $r_{\rm cyc}$ as

$$\frac{r_{\rm cyc}}{R} \approx \begin{cases} 1050 B_{12}^{1/5}\nu_9^{-1/5}\gamma_2^{-1/5}P^{2/5} & \text{for } r \lesssim r_{\rm lc} \\ 1.25 B_{12}\nu_9^{-1}\gamma_2^{-1}P^{-2} & \text{for } r > r_{\rm lc}, \end{cases} \tag{2}$$

where $R = 10^6$ cm is the radius of the neutron star, B_{12} is the strength of the magnetic field in units of 10^{12} G, $\gamma_2 = \gamma/100$, ν_9 is the radio frequency in 10^9 Hz, and P is the spin period in seconds. For a typical Lorentz factor of $\gamma \approx 100$–1000 and a plasma density of $\eta \approx 100$–1000, the cyclotron absorption radius $r_{\rm cyc}$ is always larger than the polarization-limiting radius $r_{\rm pl}$ (Barnard 1986; Wang et al. 2010). Under this scenario, the polarization-limiting radius $r_{\rm pl}$ can be estimated as

$$\frac{r_{\rm pl}}{R} \approx \begin{cases} 873\kappa_3^{1/5}B_{12}^{1/5}\nu_9^{-1/5}\gamma_2^{-3/5}P^{2/5} & \text{for } r \lesssim r_{\rm lc} \\ 0.246\kappa_3 B_{12}\nu_9^{-1}\gamma_2^{-3}P^{-2} & \text{for } r > r_{\rm lc}, \end{cases} \tag{3}$$

where $\kappa_3 = \kappa/10^3$ is the secondary plasma multiplicity. For extremely large multiplicity (e.g., $\kappa > 10^4$), $r_{\rm pl}$ can be smaller than $r_{\rm cyc}$ and is estimated using a slightly different equation according to Barnard (1986), but the difference is small and will not affect the comparison with $r_{\rm lc}$. In Figure 2, we compare $r_{\rm pl}$ and $r_{\rm cyc}$ with $r_{\rm lc}$ as a function of spin period for $B = 10^{10}$ and 10^{14} G, respectively. Shaded regions in Figure 2 show $r_{\rm pl}$ with γ in the range of 10^2–10^3, and we note that $r_{\rm pl}$ is less sensitive to κ. For Galactic magnetars and normal pulsars, their polarization-limiting and resonance radii are much smaller than the light cylinder radius as expected. For millisecond pulsars, the polarization-limiting radius is comparable to the light cylinder radius, and swept-back field lines close to the light cylinder have been suggested to explain some of the polarization features of millisecond pulsars (e.g., Barnard 1986). More importantly, we show that for pulsars with strong magnetic fields (e.g., $> 10^{14}$ G) and short spin periods (e.g., <0.01 s), $r_{\rm pl}$ and $r_{\rm cyc}$ become orders of magnitude larger than $r_{\rm lc}$. This suggests that wave mode coupling effects are negligible and will not be able to produce significant circular polarization in the magnetosphere of fast spinning magnetars.

Unlike the wave mode coupling effect, cyclotron absorption can be strong even at $r_{\rm cyc} \gg r_{\rm lc}$ if its optical depth is large. The optical depth of cyclotron absorption, τ, can be estimated as (e.g., Luo & Melrose 2001; Fussell et al. 2003)

$$\tau \approx \Gamma \epsilon\, r_{\rm cyc}/c, \tag{4}$$

where Γ is the absorption coefficient and ϵ is a parameter characterizing the radial width of the cyclotron resonance region as $\Delta r_{\rm cyc} = \epsilon r_{\rm cyc}$. As discussed in Fussell et al. (2003), ϵ depends on the plasma distribution and wave propagation angle θ and is estimated to be ~ 1 for $r_{\rm cyc} \ll r_{\rm lc}$. However, for $r_{\rm cyc} \gg r_{\rm lc}$, since the absorption coefficient drops quickly when the wave frequency deviates from the cyclotron resonance frequency, we expect ϵ to be $\ll 1$. The absorption coefficient, Γ, at the cyclotron resonance frequency, $\omega_{\rm cyc}$, can be estimated as (Fussell et al. 2003)

$$\Gamma \approx \pi \frac{\omega_{\rm p}^2}{\omega_{\rm cyc}}\theta^2, \tag{5}$$

where $\omega_{\rm p}$ is the plasma frequency. Adopting the solutions of Barnard (1986) and using their evaluations of $\omega_{\rm p}$ and $\omega_{\rm cyc}$, we can estimate the optical depth as

$$\tau \approx \begin{cases} 2700\epsilon\kappa_3\theta^2 B_{12}^{1/5}\nu_9^{-1/5}\gamma_2^{-1/5}P^{2/5} & \text{for } r \lesssim r_{\rm lc} \\ 5700\epsilon\kappa_3\theta^2 & \text{for } r > r_{\rm lc} \end{cases}. \tag{6}$$

In the case of $r < r_{\rm lc}$, τ is estimated to be ~ 1 for $\eta = 100$, $\theta = 0.1$, and $\epsilon \approx 1$, which agrees with previous results (e.g., Fussell et al. 2003; Wang et al. 2010) and suggests marginal absorption in normal pulsar magnetosphere. For $r \gg r_{\rm lc}$, which applies to fast spinning magnetars, we find that the optical depth is mainly determined by the secondary plasma multiplicity, the size of the absorption region, and the propagation angle. Although these parameters are highly uncertain at $r \gg r_{\rm lc}$, reasonable assumptions with $\epsilon \ll 1$ and $\kappa \approx 100$ give us an optical depth of ~ 1, which is necessary to explain the detection of repeating bursts. In any case, Equation (6) suggests that cyclotron absorption could be significant if the secondary plasma density is high and the absorption region is not too small outside the light cylinder.

Circular polarization can be produced by cyclotron absorption when there are asymmetries in electrons and positrons (in either their density $\Delta N/N$ or Lorentz factor $\Delta\gamma/\gamma$). As shown by Wang et al. (2010), the degree of circular polarization produced by cyclotron absorption can be estimated as

$$\frac{V}{I} \approx \frac{e^{-\Delta\tau} - 1}{e^{-\Delta\tau} + 1}, \tag{7}$$

where $\Delta\tau$ is the difference in optical depth of electrons and positrons. $\Delta\tau$ is determined by $\Delta N/N$ and $\Delta\gamma/\gamma$ as

$$\Delta\tau = 2\tau\left(\frac{\Delta N}{N} - \frac{\Delta\gamma}{6\gamma}\right). \quad (8)$$

In Figure 3 we show the degree of circular polarization as a function of optical depth for different $\Delta N/N$ and $\Delta\gamma/\gamma$. We can see that high degrees of circular polarization can only be produced when both the optical depth and asymmetry in electrons and positrons are large. For marginal absorption ($\tau \sim 1$) and low levels of asymmetry ($\Delta N/N \sim 10^{-2}$ and $\Delta\gamma/\gamma \sim 10^{-2}$), the expected circular polarization is only a few percent.

5. Discussion and Conclusions

In this paper, we investigated wave mode coupling and cyclotron absorption effects in the magnetosphere of fast spinning magnetars, one of the promising origins of repeating FRBs. We show that the polarization-limiting radius is much larger than the radius of the light cylinder of fast spinning magnetars, and therefore wave mode coupling is unlikely to produce significant circular polarization. Depending on the secondary plasma density and the size of the absorption region, cyclotron absorption could be strong outside the light cylinder, but high degrees of circular polarization can only be produced if the asymmetry in electrons and positrons is unusually high (e.g., $\Delta N/N \gg 10^{-2}$). Our results suggest that it is challenging for propagation effects commonly discussed for radio pulsars to produce strong circular polarization in the case of fast spinning magnetars.

Our discussion is focused on propagation effects in the magnetosphere of fast spinning magnetars and assumes that the radio emission originates within the magnetosphere. This is one of the many FRBs models and possibly one of the many emission channels under the magnetar model (e.g., Lu et al. 2020). We did not explore the origin of circular polarization observed in non-repeating FRBs and argue that non-repeating FRBs might involve different radiation mechanisms. We suggest that the difference in polarization property of repeating and non-repeating FRBs, together with their diverse burst morphology, can be a key discriminant of their origins and radiation mechanisms. If non-repeating FRBs are also powered by fast spinning magnetars, we argue that their high degrees of circular polarization cannot be explained by propagation effects within the magnetosphere, and other effects, such as Faraday conversion in dense and magnetized environments (Gruzinov & Levin 2019), are required.

The current sample of repeating FRBs with deep polarization observation is still limited. As more FRBs are being discovered (e.g., Macquart et al. 2010; Sanidas et al. 2018; Kocz et al. 2019; Zhu et al. 2020; CHIME/FRB Collaboration et al. 2021; Niu et al. 2021), highly sensitive polarization observations of repeating FRBs will enable us to test models of the FRB central engine and radiation mechanism. If repeating FRBs are all powered by fast spinning magnetars, we expect to see low degrees (close to zero) of circular polarization despite deep observations. Even if circular polarization can be detected in some repeating FRBs, the distribution of fractional circular polarization can be compared with those of non-repeating FRBs and Galactic magnetars. A statistically lower fractional circular polarization of repeating FRBs will provide support to models that involve different origins and/or radiation mechanisms for repeating and non-repeating FRBs. Ultimately, if sub-second rotational periodicity is detected in repeating FRBs, propagation effects in the magnetosphere of fast spinning magnetars can be studied through variations of circular and linear polarization across the pulse (e.g., Wang et al. 2010).

The origin and many observational properties of circular polarization of normal radio pulsars are still not fully understood (e.g., Johnston & Kerr 2018; Ilie et al. 2019; Dyks et al. 2021). It is even harder to understand those of millisecond pulsars (e.g., Dai et al. 2015) as their polarization-limiting regions are close to the light cylinder (e.g., Jones 2020). Despite the detection of strong circular polarization from radio-loud magnetars, their origin and properties have not been investigated in the literature. For magnetars with short spin periods, effects arising in highly magnetized vacuum or highly relativistic plasma can be important (e.g., Kennett & Melrose 1998). The properties of the plasma and magnetic fields both inside and outside the light cylinder of magnetars are not clear, which can significantly affect our treatment of propagation effects. The asymmetry in electrons and positrons can also be much larger in pulsar magnetospheres generating FRBs (e.g., Kumar et al. 2017; Wang et al. 2019), which implies that the circularization effect can be more important than for radio pulsars. It is beyond the scope of this paper to develop a comprehensive model for the magnetosphere of fast spinning magnetars, but theoretical studies of this special case should be encouraged, especially considering its potential link with repeating FRBs.

The detection of an extremely intense radio burst (FRB 200428) from the Galactic magnetar SGR 1935+2154 provides strong support for the theory that magnetars are the origin of at least some FRBs (Bochenek et al. 2020; CHIME/FRB Collaboration et al. 2020). Despite the extreme intensity and strong linear polarization, no significant circular polarization was detected in FRB 200428 (CHIME/FRB Collaboration et al. 2020). A few days after the initial event, Zhang et al. (2020) detected a much fainter burst from SGR 1935+2154 with a high degree of linear polarization but no evidence of circular polarization. Two more bursts from SGR 1935+2154 were detected in 2020 May, and one of them shows some degree of circular polarization (Kirsten et al. 2021a). As a 3.2 s magnetar with a surface magnetic field strength of $B \approx 2.2 \times 10^{14}$ G (Israel et al. 2016), we expect the propagation effects in the magnetosphere of SGR 1935+2154 to be significant and its polarization properties to be similar to those of other Galactic magnetars. Further studies of the polarization properties of Galactic magnetars will provide us insights into their magnetic field structure and plasma properties. For example, Tong et al. (2021) recently discussed the modification of the rotating vector model in the case of magnetars with twisted magnetic fields.

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