The Pulsar Gamma-Ray Emission from High-resolution Dissipative Magnetospheres

Gang Cao and Xiongbang Yang

Department of Mathematics, Yunnan University of Finance and Economics, Kunming 650221, Yunnan, People’s Republic of China; gcao@ynufe.edu.cn

Received 2021 March 9; revised 2021 November 18; accepted 2021 November 20; published 2022 February 1

Abstract

The pulsar light curves and energy spectra in dissipative pulsar magnetospheres are explored with Aristotelian electrodynamics (AE), where particle acceleration is fully balanced with the radiation reaction. AE magnetospheres with nonzero pair multiplicity are computed using a pseudo-spectral method in the co-moving frame. The dissipative region near the current sheet outside the light cylinder is accurately captured by a high-resolution simulation. The pulsar light curves and spectra are computed using the test particle trajectory method, including the influence of both the consistent accelerating electric field and radiation reaction. Our results can generally reproduce the double-peak light curves and the GeV cutoff energy spectra in agreement with the Fermi observations for the pair multiplicity \( \kappa \geq 1 \).

Unified Astronomy Thesaurus concepts: Gamma-rays (637); Magnetic fields (994); Pulsars (1306)

1. Introduction

The Fermi Gamma-Ray Space Telescope launched in 2008 opened a new era of the study of pulsar \( \gamma \)-ray emission. To date, Fermi-LAT has detected more than 270 \( \gamma \)-ray pulsars,\(^1\) of which are listed in the Second Fermi Pulsar Catalog (Abdo et al. 2010, 2013). Fermi \( \gamma \)-ray pulsars are classified into three groups: young radio-loud, young radio-quiet, and millisecond pulsars. Light curves from these pulsars usually show widely separated double-peak profiles, and the first peak lags the radio peak by a small fraction of rotation period. The pulsar \( \gamma \)-ray spectra can be described by a power law with an exponential cutoff, and the cutoff energy is in the range of \( 1-5 \) GeV. The light curves and energy spectra from Fermi-LAT offer a unique opportunity to explore the nature of the radiation mechanisms and the location of particle acceleration in the magnetosphere. However, the origin of pulsar emission is still unclear. In fact, the pulsed emission and particle acceleration in the magnetosphere are controlled by the structure of the global pulsar magnetosphere. This requires us to have a deep and accurate knowledge of the pulsar magnetosphere. Significant progress has been made in the development of a numerical model of global pulsar magnetospheres over the last decades.

It is widely believed that the pulsar magnetosphere is loaded with plasmas by pair creation (Goldreich & Julian 1969). A zeroth order approximation of the plasma-filled magnetosphere is referred to as the force-free electrodynamics (FFE). The force-free approximation requires a density number much larger than Goldreich-Julian density; these plasmas quickly short out the accelerating fields so that the force-free condition \( E \cdot B = 0 \) holds everywhere. The force-free pulsar magnetosphere has recently been achieved with the advent of numerical simulations. The numerical force-free solution was first obtained by Contopoulos et al. (1999, hereafter CKF) for the aligned rotator and then by Spitkovsky (2006) for the oblique rotator. 3D force-free solutions are further explored by the finite-difference time-domain method (Kalapotharakos & Contopoulos 2009; Contopoulos & Kalapotharakos 2010) and the spectral method (Pétri 2012; Cao et al. 2016a, 2016b; Pétri 2016). All these time-dependent force-free simulations confirmed the existence of the current sheet outside the light cylinder (LC), which is thought to be a potential site of the pulsar \( \gamma \)-ray emission. The pulsar light curves and spectra are also studied by placing the emission region in the current sheet outside the LC (Bai & Spitkovsky 2010; Brambilla et al. 2015; Harding & Kalapotharakos 2015; Bogovalov et al. 2018; Harding et al. 2018). However, the force-free solution does not allow any particle acceleration and the production of the pulsed radiation in the magnetosphere.

A more realistic pulsar model should allow the local dissipation to produce the observed pulsar phenomena. The dissipative effects have been included by involving a finite conductivity (Kalapotharakos et al. 2012a; Li et al. 2012; Cao et al. 2016b), which is called the resistive magnetosphere. The resistive magnetosphere ranges from the vacuum limit to the force-free limit with increasing conductivity, and the resistive solution produces accelerating electric fields that are self-consistent with the magnetic field structure. The resistive magnetospheres have been used to model the pulsar light curves (Kalapotharakos et al. 2012b, 2014, 2017; Cao & Yang 2019) and energy spectra (Yang & Cao 2021) by including the accelerating electric field from the simulation. These studies have suggested that the particle acceleration and the \( \gamma \)-ray radiation is produced near the current sheets outside the LC. Recently, particle-in-cell (PIC) methods have been developed to model the pulsar magnetosphere by self-consistently treating the feedback between the particle motion and the electromagnetic fields (Chen & Beloborodov 2014; Philippov & Spitkovsky 2014; Belyaev 2015; Cerutti et al. 2015; Philippov et al. 2015; Brambilla et al. 2018; Kalapotharakos et al. 2018). Moreover, the pulsar light curves are predicted by extracting particle radiation along each trajectory in a full PIC simulation (Cerutti et al. 2016; Kalapotharakos et al. 2018; Philippov & Spitkovsky 2018). However, the particle energy from the PIC simulation is much smaller than those in the real pulsar, which is not enough to produce the observed Fermi \( \gamma \)-ray emission.

---

\(^1\) https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
A good approximation between the resistive model and the PIC model is Aristotelian electrodynamics (AE), which can include the backreaction of the emitting photons onto particle motions and allow for some dissipation in the magnetosphere. The AE method was first introduced by Gruzinov (2012, 2013) to study the pulsar magnetosphere. Recently, a clever method by combining FFE with AE has been proposed to construct the structure of the pulsar magnetosphere (Contopoulos 2016; Pétri 2019; Cao & Yang 2020). Contopoulos (2016) first presented the 3D structure of the AE magnetosphere for the oblique rotator using the finite-difference method. However, they only studied the AE solution in the limit of no pair multiplicity. Pétri (2019) extended the study of Contopoulos (2016) by introducing nonzero pair multiplicity and used the spectral method to compute the AE magnetosphere but only for the aligned rotator. Recently, Cao & Yang (2020) presented the first AE solution with nonzero pair multiplicity for the oblique rotator by the spectral method. They show that the dissipative region becomes more restricted to the current sheet outside the LC as the pair multiplicity increases. However, a relatively low resolution is generally used in all these simulations, which is not enough to accurately capture the current sheet outside the LC. Moreover, the light curves and spectra were not computed from the numerical AE solutions in all these studies. In this paper, we present a high-resolution simulation of the AE magnetosphere with nonzero pair multiplicity for the oblique rotator using the spectral method. The pulsar light curves and spectra are then computed using the test particle trajectory method in a dissipative AE magnetosphere. The paper is organized as follows: We describe the AE model in Section 2. We present the pulsar light curves and spectra from the AE magnetosphere in Section 3. A brief discussion and conclusions are presented in Section 4.

2. AE Model

It is difficult to determine whether the magnetosphere has reached a steady state at the end of the simulation, especially for the oblique rotator in which all the field lines remain time dependent in the observer frame. Therefore, it is useful to study the pulsar magnetosphere for the stationary state in the comoving frame, in which the magnetosphere relaxes to the time-independent solution where all the field lines remain time independent. The time-dependent Maxwell equations in the comoving frame are given by Muslimov & Harding (2005) and by using different filter parameters, where $E_0$ is the unit of the stellar surface magnetic field.

$$\frac{\partial B}{\partial t'} = -\nabla \times (E + V_{rot} \times B),$$

$$\frac{\partial E}{\partial t'} = \nabla \times (B - V_{rot} \times E) - J + V_{rot} \nabla \cdot E,$$  

$$\nabla \cdot B = 0,$$  

$$\nabla \cdot E = \rho_e,$$

where $V_{rot} = \Omega \times r$ is the corotation velocity. $\rho_e$ and $J$ are the charge density and the current density, respectively. It is noted that $E$ and $B$ are still defined in the observed frame. The pulsar magnetosphere can be computed by implementing a prescription for the current density $J$.

The pulsar magnetosphere cannot be surrounded by vacuum because the rotating vacuum solution produces an accelerating electric field that is able to extract the particles from the stellar surface and fill the magnetosphere. Therefore, realistic pulsar...
magnetospheres require the presence of plasma and have some dissipation regions to produce the particle acceleration and the pulsed radiation. The backreaction of the emitted photons onto the particle motion occurs in a direction opposite to its motion. This process can be easily treated by assuming a stationary balance between the particle acceleration and radiation, i.e., $AE$. The current density in the $AE$ magnetosphere can be defined by introducing the pair multiplicity $\kappa$ as

$$J_{EBBE} = \kappa \frac{E_0 B + E_0 E}{B^2 + E_0^2}.$$

where $B_0$ and $E_0$ are the magnetic and electric field in the frame in which $E$ and $B$ are parallel. The quantities $B_0$ and $E_0$ are given by the relations

$$B_0^2 - E_0^2 = B^2 - E^2,$$

$$E_0 B_0 = E \cdot B,$$

with $E_0 \geq 0$.

The force-free approximation satisfies the force-free condition $E \cdot B = 0$ and requires the condition $E \leq B$ in the whole magnetosphere. The current sheet is captured by enforcing the condition $E = B$ in the regions where $E > B$. Therefore, the force-free approximation cannot produce any dissipative regions where $E > B$. However, the AE model can allow for dissipation in some regions where $E > B$. It is well known that the pulsar magnetosphere should allow for a local dissipation to produce the pulsed emission. Recent numerical simulations have shown that the current sheet is a promising site for particle acceleration and high-energy radiation in the magnetosphere. To explore the dissipation where $E > B$, we use the force-free description where $E \leq B$ and the AE description where $E > B$. It is expected that our model will produce the dissipative region with $E > B$ outside the LC.

3. Result

3.1. Magnetospheric Structure

The time-dependent Maxwell equations are solved by a spectral algorithm in the co-moving frame with the combined FFE and AE description. The electromagnetic field is discretized by a set of spectral collocation points in spherical coordinates $(r, \theta, \phi)$. The radial components of the electromagnetic field are expanded onto the Chebyshev polynomial, and the angle components are expanded onto the vector spherical harmonic expansion. We improve the time integration described in Cao & Yang (2020) by using a combined three-order Runge–Kutta and Adam–Bashforth method. An exponential filter with $\sigma(\eta) = \exp(-\alpha |\eta|)$ in all directions is used to smooth the electromagnetic field at each time step. The divergenceless condition on the magnetic field is analytically enforced by a projection method. The simulation is initialized with a dipole magnetic field and a zero electric field outside the star. We enforce the inner boundary condition at the stellar surface with a rotating electric field $E = -(\Omega \times r) \times B/c$. We use a nonreflecting boundary condition to prevent reflection.
from the outer boundary. The simulation domain is set to $r \in (0.2–3) r_L$. A high resolution with $N_r \times N_\theta \times N_f = 129 \times 64 \times 128$ is used to catch the current sheet in all simulations. We performed several simulations for magnetic inclination angle $\chi = \{0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ\}$ with the pair multiplicity $\kappa = \{0, 1, 3\}$. The system is evolved for several rotational periods to ensure that a steady solution has been reached.

A spectral filter is necessary to prevent Gibbs oscillation and nonlinear instabilities in the spectral algorithm. A nonphysical dissipation is introduced by the filtering processes. It is difficult to correctly catch the discontinuity induced by the current sheet, which can be circumvented by increasing the simulation resolution and adjusting the spectral filter. We show the distribution of the magnetic field line and the accelerating electric field $E_0$ in the $x$–$z$ plane for a $60^\circ$ rotator with the pair multiplicity $\kappa = 1$ by using different filter parameters, as shown in Figure 1. We see that all solutions have similar $E_0$ distributions in the current sheet, and they are independent of the choice of a filter. A low-order filter with $(\alpha, \beta) = (10, 6)$ gives a more dissipation solution with large numerical diffusion in the current sheet than a high-order filter with $(\alpha, \beta) = (10, 8)$ and $(\alpha, \beta) = (36, 8)$. A more accurate solution can be obtained by using a optimized filtering parameter $(\alpha, \beta) = (10, 8)$ with a high-order filter and a suitable $\alpha$ value. The normalized Poynting flux $L/L_{\text{aligned}}$ as a function of radius $r$ for a $60^\circ$ rotator with different pair multiplicities is shown in Figure 2. For comparison, we also show the normalized Poynting flux with the pair multiplicity $\kappa = 1$ for the low-resolution simulation and the same optimized filtering parameter, as shown by the red dashed line in Figure 2. It is found that the Poynting flux increases with increasing $\kappa$ values and approaches the force-free solution for the high $\kappa$ value. It is expected that there is no dissipation inside the LC in the combined FFE and AE magnetosphere. We see that the high-resolution simulation shows smaller dissipation in the LC.

Figure 4. Distributions of the magnetic field lines and the accelerating electric field $E_0$ for different magnetic inclination angles with the pair multiplicity $\kappa = 3$ in the $x$–$z$ plane, where $E_0$ is the unit of the stellar surface magnetic field.

Figure 5. The curvature radiation spectra for a $60^\circ$ magnetosphere with the pair multiplicities $\kappa = \{0, 1, 3\}$. From the outer boundary. The simulation domain is set to $r \in (0.2–3) r_L$. A high resolution with $N_r \times N_\theta \times N_f = 129 \times 64 \times 128$ is used to catch the current sheet in all simulations. We performed several simulations for magnetic inclination angle $\chi = \{0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ\}$ with the pair multiplicity $\kappa = \{0, 1, 3\}$. The system is evolved for several rotational periods to ensure that a steady solution has been reached.

A spectral filter is necessary to prevent Gibbs oscillation and nonlinear instabilities in the spectral algorithm. A nonphysical dissipation is introduced by the filtering processes. It is difficult to correctly catch the discontinuity induced by the current sheet, which can be circumvented by increasing the simulation resolution and adjusting the spectral filter. We show the distribution of the magnetic field line and the accelerating electric field $E_0$ in the $x$–$z$ plane for a $60^\circ$ rotator with the pair multiplicity $\kappa = 1$ by using different filter parameters, as shown in Figure 1. We see that all solutions have similar $E_0$ distributions in the current sheet, and they are independent of the choice of a filter. A low-order filter with $(\alpha, \beta) = (10, 6)$ gives a more dissipation solution with large numerical diffusion in the current sheet than a high-order filter with $(\alpha, \beta) = (10, 8)$ and $(\alpha, \beta) = (36, 8)$. A more accurate solution can be obtained by using a optimized filtering parameter $(\alpha, \beta) = (10, 8)$ with a high-order filter and a suitable $\alpha$ value. The normalized Poynting flux $L/L_{\text{aligned}}$ as a function of radius $r$ for a $60^\circ$ rotator with different pair multiplicities is shown in Figure 2. For comparison, we also show the normalized Poynting flux with the pair multiplicity $\kappa = 1$ for the low-resolution simulation and the same optimized filtering parameter, as shown by the red dashed line in Figure 2. It is found that the Poynting flux increases with increasing $\kappa$ values and approaches the force-free solution for the high $\kappa$ value. It is expected that there is no dissipation inside the LC in the combined FFE and AE magnetosphere. We see that the high-resolution simulation shows smaller dissipation in the LC.
compared to the low-resolution simulation. Our simulation shows that the dissipative region in the current sheet can be better resolved by both increasing the grid resolution and controlling the filtering effect in our spectral algorithm. It is noted that the low-resolution simulation and/or the high-resolution simulation with the strong spectral filter show more dissipative accelerating regions in the current sheet, which produces the higher cutoff energy in the curvature radiation spectrum.

We show the distribution of the magnetic field line and the accelerating electric field $E_0$ for a $60^\circ$ rotator with the pair multiplicity $\kappa = \{0, 1, 3\}$ and the optimized filtering

Figure 6. The sky maps and the corresponding light curves at $>1$ GeV energies at different inclination angles and view angles with the pair multiplicity $\kappa = 3$. 

Cao & Yang
parameters \( (\alpha, \beta) = (10, 8) \) in the \( x-z \) and \( x-y \) plane, as shown in Figure 3. As the pair multiplicity \( \kappa \) increases, the magnetosphere tends to the force-free solution with a current sheet outside the LC. We observe a strong \( E_0 \) region with \( E > B \) outside the LC. The dissipative region decreases with increasing pair multiplicity and the dissipative region is more confined to the near the current sheet outside the LC for the high pair multiplicity. We also show the distribution of the magnetic field line and the accelerating electric field \( E_0 \) for different inclination angles with the pair multiplicity \( \kappa = 3 \) in the \( x-z \) plane, as shown in Figure 4. We see that all solutions have a near force-free magnetosphere with the dissipative region only near the current sheet for all the inclination angles. Our high-resolution simulation with the optimized filtering parameter gives a more accurate solution near the current sheet compared to those in Cao & Yang (2020) and Pétri (2020).

### 3.2. Light Curves and Energy Spectra

The particle velocity in the radiation reaction limit is defined by Gruzinov (2012, 2013) as

\[
v_{\perp} = \frac{E \times B \pm (B_0 B + E_0 E)}{B^2 + E_0^2},
\]

where the two signs correspond to positrons and electrons, and they react to electromagnetic fields in different ways in the AE magnetosphere. The Lorentz factor along particle trajectory is given by

\[
\frac{d\gamma}{dt} = \frac{q_e c E_0}{m_e c^2} - \frac{2q_e^2 \gamma^4}{3R_{CR} m_e c}.
\]

The photon spectrum of curvature radiation for each particle with Lorentz factor \( \gamma \) is given

\[
F(E_{\gamma}, r) = \frac{\sqrt{3} e^{2\gamma}}{2\pi / R_{CR} E_{\gamma}} F(x),
\]

where \( x = E_{\gamma} / E_{cut}, \) \( E_{\gamma} \) is the radiation photon energy, \( E_{cut} = \frac{3}{2} c^3 h / R_{CR} \) is the characteristic energy of the curvature radiation photon, \( R_{CR} \) is the curvature radius of particles, and the function \( F(x) \) is defined as

\[
F(x) = x \int_x^{\infty} K_{5/3}(\xi) \, d\xi,
\]

The initial particles are randomly injected from the polar caps on the stellar surface with small Lorentz factor. The particle trajectory is determined by integrating the particle velocity from the the neutron star surface up to \( r = 2.5 r_{\perp} \). The Lorentz factor along each trajectory is then computed under the influence of the local accelerating electric field and the curvature radiation loss. Assuming that the direction of the photon emission is along the direction of the particle motion, we can compute the direction of the photon emission and the curvature radiation spectrum along each trajectory. The pulsar light curves and spectra can be constructed by collecting all curvature radiation photons along each particle in sky maps.

We show the curvature radiation spectra for a 60° magnetosphere with different pair multiplicities \( \kappa = \{0, 1, 3\} \) in Figure 5. It can be seen that our model can produce a power-law spectrum with an exponential cutoff. Moreover, the cutoff energy decreases as the pair multiplicity \( \kappa \) increases, which is caused by the decrease of the accelerating electric field in the dissipative region outside the LC. We also find that the cutoff energy lies in the range of 1–5 GeV for the pair multiplicity \( \kappa \geq 1 \), which is consistent with the Fermi observed GeV cutoff energy. We also find that the spectra for all the inclination angles are very similar to those presented in Figure 5. We show the sky maps and the corresponding light curves in different inclination angles and view angles with the pair multiplicity \( \kappa = 3 \) in Figure 6. We see that the double-peak light curves can generally be produced for a broad range of inclination angles and view angles, which are generally in agreement with those observed by Fermi-LAT. Our results support that the observed \( \gamma \)-ray pulsar population is consistent with curvature radiation (Kalapotharakos et al. 2019).

### 4. Discussion and Conclusions

We first explore the properties of the pulsar light curves and energy spectra in dissipative AE magnetospheres. The dissipative AE magnetospheres with nonzero pair multiplicity are presented by a pseudo-spectral method with the high-resolution simulations in the co-moving frame. Our simulations show that the dissipative region near the current sheet outside the LC can be accurately captured by the high-resolution simulation. We use these field structures to define the trajectory of the positrons and electrons with the radiation reaction. The pulsar light curves and energy spectra are then produced by collecting all curvature radiation photons along each particle trajectory. Our results show that the double-peak light curves and the power-law energy spectra with an exponential cutoff at ~1 GeV energy range can generally be produced for a moderate pair multiplicity \( \kappa \geq 1 \), which are well consistent with those observed by Fermi-LAT.

Our study provide the first step to model the pulsar emission for direct comparison with observation by including consistent accelerating electric field and radiation reaction from the dissipative AE magnetosphere. It is necessary to perform more magnetosphere simulations with a broader range of the magnetic inclination and pair multiplicity to construct the pulsar light curves and spectra, which would allow us to directly compare them with the Fermi observations. This comparison would provide meaningful constraints on the model parameters and enhance our understanding of the physical mechanisms of pulsar \( \gamma \)-ray emission. We will present the detailed comparisons with the Fermi observational data in the near future.

We thank the anonymous referee for valuable comments and suggestions. We would like to thank Jérôme Pétri and Ioannis Contopoulos for some useful discussions. We acknowledge the financial support from the National Natural Science Foundation of China 12003026, and the Basic research Program of Yunnan Province 202001AU070070.

**ORCID iDs**

Xiongbang Yang @ https://orcid.org/0000-0002-1496-3209

**References**

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJS, 187, 460
Abdo, A. A., Ajello, M., Allafort, A., et al. 2013, ApJS, 208, 17
Bai, X. N., & Spitkovsky, A. 2010, ApJ, 715, 1282
The Astrophysical Journal, 925:130 (7pp), 2022 February 1

Cao & Yang

Kalapotharakos, C., Brambilla, G., Timokhin, A., Harding, A. K., & Kazanas, D. 2018, ApJ, 857, 44
Kalapotharakos, C., & Contopoulos, I. 2009, A&A, 496, 495
Kalapotharakos, C., Harding, A. K., & Kazanas, D. 2014, ApJ, 793, 97
Kalapotharakos, C., Harding, A. K., Kazanas, D., & Brambilla, G. 2017, ApJ, 842, 80
Kalapotharakos, C., Harding, A. K., Kazanas, D., & Contopoulos, I. 2012b, ApJL, 754, L1
Kalapotharakos, C., Harding, A. K., Kazanas, D., & Wadiasingh, Z. 2019, ApJL, 883, L4
Kalapotharakos, C., Kazanas, D., Harding, A., & Contopoulos, I. 2012a, ApJ, 749, 2
Li, J., Spitkovsky, A., & Tchekhovskoy, A. 2012, ApJ, 746, 60
Muslimov, A. G., & Harding, A. K. 2005, ApJ, 630, 454
Pétrí, J. 2012, MNRAS, 424, 605
Pétrí, J. 2016, MNRAS, 455, 3779
Pétrí, J. 2019, MNRAS, 484, 5669
Pétrí, J. 2020, Univ, 6, 15
Philippov, A. A., & Spitkovsky, A. 2014, ApJ, 785, L33
Philippov, A. A., & Spitkovsky, A. 2018, ApJ, 855, 94
Philippov, A. A., Spitkovsky, A., & Cerutti, B. 2015, ApJ, 801, L19
Spitkovsky, A. 2006, ApJ, 648, L51
Yang, X. B., & Cao, G. 2021, ApJ, 909, 88

Belyaev, M. A. 2015, MNRAS, 449, 2759
Bogovalov, S. V., Contopoulos, I., Prosekin, A., Tronin, I., & Aharonian, F. A. 2018, MNRAS, 476, 4213
Brambilla, G., Harding, A. K., Kalapotharakos, K., & Kazanas, D. 2015, ApJ, 804, 84
Brambilla, G., Kalapotharakos, K., Timokhin, A. N., Harding, A. K., & Kazanas, D. 2018, ApJ, 858, 81
Cao, G., & Yang, X. B. 2019, ApJ, 874, 166
Cao, G., & Yang, X. B. 2020, ApJ, 889, 29
Cao, G., Zhang, L., & Sun, S. N. 2016a, MNRAS, 455, 4267
Cao, G., Zhang, L., & Sun, S. N. 2016b, MNRAS, 461, 1068
Cerutti, B., Philippov, A., Parfrey, K., & Spitkovsky, A. 2015, MNRAS, 448, 606
Cerutti, B., Philippov, A. A., & Spitkovsky, A. 2016, MNRAS, 457, 2401
Chen, A. Y., & Beloborodov, A. M. 2014, ApJ, 795, L22
Contopoulos, I. 2016, MNRAS, 463, L94
Contopoulos, I., & Kalapotharakos, C. 2010, MNRAS, 404, 767
Contopoulos, I., Kazanas, D., & Fendt, C. 1999, ApJ, 511, 351
Goldreich, P., & Julian, W. H. 1969, ApJ, 157, 869
Gruzinov, A. 2012, arXiv:1205.3367
Gruzinov, A. 2013, arXiv:1303.4094
Harding, A. K., & Kalapotharakos, C. 2015, ApJ, 811, 63
Harding, A. K., Kalapotharakos, C., Barnard, M., & Venter, C. 2018, ApJ, 869, L18

The Astrophysical Journal, 925:130 (7pp), 2022 February 1

Kalapotharakos, C., Brambilla, G., Timokhin, A., Harding, A. K., & Kazanas, D. 2018, ApJ, 857, 44
Kalapotharakos, C., & Contopoulos, I. 2009, A&A, 496, 495
Kalapotharakos, C., Harding, A. K., & Kazanas, D. 2014, ApJ, 793, 97
Kalapotharakos, C., Harding, A. K., Kazanas, D., & Brambilla, G. 2017, ApJ, 842, 80
Kalapotharakos, C., Harding, A. K., Kazanas, D., & Contopoulos, I. 2012b, ApJL, 754, L1
Kalapotharakos, C., Harding, A. K., Kazanas, D., & Wadiasingh, Z. 2019, ApJL, 883, L4
Kalapotharakos, C., Kazanas, D., Harding, A., & Contopoulos, I. 2012a, ApJ, 749, 2
Li, J., Spitkovsky, A., & Tchekhovskoy, A. 2012, ApJ, 746, 60
Muslimov, A. G., & Harding, A. K. 2005, ApJ, 630, 454
Pétrí, J. 2012, MNRAS, 424, 605
Pétrí, J. 2016, MNRAS, 455, 3779
Pétrí, J. 2019, MNRAS, 484, 5669
Pétrí, J. 2020, Univ, 6, 15
Philippov, A. A., & Spitkovsky, A. 2014, ApJ, 785, L33
Philippov, A. A., & Spitkovsky, A. 2018, ApJ, 855, 94
Philippov, A. A., Spitkovsky, A., & Cerutti, B. 2015, ApJ, 801, L19
Spitkovsky, A. 2006, ApJ, 648, L51
Yang, X. B., & Cao, G. 2021, ApJ, 909, 88

Belyaev, M. A. 2015, MNRAS, 449, 2759
Bogovalov, S. V., Contopoulos, I., Prosekin, A., Tronin, I., & Aharonian, F. A. 2018, MNRAS, 476, 4213
Brambilla, G., Harding, A. K., Kalapotharakos, K., & Kazanas, D. 2015, ApJ, 804, 84
Brambilla, G., Kalapotharakos, K., Timokhin, A. N., Harding, A. K., & Kazanas, D. 2018, ApJ, 858, 81
Cao, G., & Yang, X. B. 2019, ApJ, 874, 166
Cao, G., & Yang, X. B. 2020, ApJ, 889, 29
Cao, G., Zhang, L., & Sun, S. N. 2016a, MNRAS, 455, 4267
Cao, G., Zhang, L., & Sun, S. N. 2016b, MNRAS, 461, 1068
Cerutti, B., Philippov, A., Parfrey, K., & Spitkovsky, A. 2015, MNRAS, 448, 606
Cerutti, B., Philippov, A. A., & Spitkovsky, A. 2016, MNRAS, 457, 2401
Chen, A. Y., & Beloborodov, A. M. 2014, ApJ, 795, L22
Contopoulos, I. 2016, MNRAS, 463, L94
Contopoulos, I., & Kalapotharakos, C. 2010, MNRAS, 404, 767
Contopoulos, I., Kazanas, D., & Fendt, C. 1999, ApJ, 511, 351
Goldreich, P., & Julian, W. H. 1969, ApJ, 157, 869
Gruzinov, A. 2012, arXiv:1205.3367
Gruzinov, A. 2013, arXiv:1303.4094
Harding, A. K., & Kalapotharakos, C. 2015, ApJ, 811, 63
Harding, A. K., Kalapotharakos, C., Barnard, M., & Venter, C. 2018, ApJ, 869, L18