DC CIRCUIT POWERED BY ORBITAL MOTION: MAGNETIC INTERACTIONS IN COMPACT OBJECT BINARIES AND EXOPLANETARY SYSTEMS

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ABSTRACT

The unipolar induction DC circuit model, originally developed by Goldreich and Lynden-Bell for the Jupiter–Io system, has been applied to different types of binary systems in recent years. We show that there exists an upper limit to the magnetic interaction torque and energy dissipation rate in such a model. This arises because when the resistance of the circuit is too small, the large current flow severely twists the magnetic flux tube connecting the two binary components, leading to the breakdown of the circuit. Applying this limit, we find that in coalescing neutron star binaries, magnetic interactions produce negligible correction to the phase evolution of the gravitational waveform, even for magnetar-like field strengths. However, energy dissipation in the binary magnetosphere may still give rise to electromagnetic radiation prior to the final merger. For ultracompact white dwarf binaries, we find that unipolar induction does not provide adequate energy dissipation to explain the observed X-ray luminosities of several sources. For exoplanetary systems containing close-in Jupiters or super-Earths, the magnetic torque and energy dissipation induced by the orbital motion are negligible, except possibly during the early T Tauri phase, when the stellar magnetic field is stronger than $10^3$ G.

Key words: binaries: close – gravitational waves – planetary systems – stars: magnetic field – stars: neutron

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1. INTRODUCTION

In a seminal paper, Goldreich & Lynden-Bell (1969) developed a DC circuit model for the magnetic interaction between Jupiter and its satellite Io (see also Piddington & Drake 1968). In this model, the orbital motion of Io in the rotating magnetosphere of Jupiter generates electromotive force (EMF), driving a DC current between Io and Jupiter, with the closed magnetic field lines serving as wires. In essence, the Jupiter–Io system operates as a unipolar inductor. This model helped explain Jupiter’s decametric radio emissions which are correlated with the motion of Io and the hot spot in Jupiter’s atmosphere that is linked magnetically to Io (e.g., Clarke et al. 1996).

In recent years, the DC circuit model of Goldreich & Lynden-Bell has been adapted and applied to other types of astrophysical binary systems, including (1) planets around magnetic white dwarfs (WD; Li et al. 1998); (2) ultracompact WD binaries with periods ranging from a few minutes to an hour (Wu et al. 2002; Dall’Osso et al. 2006, 2007); (3) coalescing neutron star (NS)–black hole (BH) binaries and NS–NS binaries prior to the final merger (McWilliams & Levin 2011; Piro 2012; see also Vietri 1996, Hansen & Lyutikov 2001, and Lyutikov 2011 for more general discussion of unipolar induction in such binaries); and (4) exoplanetary systems containing short-period (∼days) planets orbiting magnetic MS stars (Laine & Lin 2012; Zarka 2007).

In the DC circuit model, the magnetic interaction torque and the related energy dissipation rate are inversely proportional to the total resistance $R_{\text{tot}}$ of the circuit, including contributions from the two binary components and the magnetosphere. Thus, it seems that extreme power may be produced for highly conducting binary systems. However, we show in this paper that when $R_{\text{tot}}$ is smaller than a critical value (∼480 $v_{\text{rel}}/c$ Ohms, where $v_{\text{rel}}$ is the orbital velocity as seen in the rotating frame of the magnetic star), the large current flowing in the circuit will break the magnetic connection between the binary components. Thus, there exists an upper limit to the magnetic torque and the energy dissipation rate. In Sections 2–4, we examine the general aspect of the DC circuit model, the upper limit, and its connection with "open circuit" effect ("Alfvén radiation"). We then discuss applications of the model to various astrophysical binaries in Sections 5–8 and conclude in Section 9.

2. DC CIRCUIT MODEL OF MAGNETIC INTERACTION

Consider a binary system consisting of a magnetic star (the "primary," with mass $M_*$, radius $R_*$, spin $\Omega_*$, and magnetic dipole moment $\mu$) and a non-magnetic companion (mass $M_c$, radius $R_c$). The orbital separation is $a$ and the orbital angular frequency is $\Omega$. The magnetic field strength at the surface of the primary is $B_*=\mu/R_*^3$. The whole binary system is embedded in a tenuous plasma (magnetosphere). For simplicity, we assume $\Omega_*, \Omega_c, \text{ and } \mu$ are all aligned.

The motion of the non-magnetic companion relative to the magnetic field of the primary produces an EMF $E \simeq 2\mu R_c |\dot{\Omega}|$, where $E = v_{\text{rel}} \times B/\mu$, with $v_{\text{rel}} = (\Omega - \Omega_c) a \hat{\phi}$ and $B = (-\mu/a^3) \hat{z}$. This gives

$$E \simeq \frac{2\mu R_c}{a^2} \Delta \Omega,$$

where $\Delta \Omega = \Omega - \Omega_c$. The EMF drives a current along the magnetic field lines in the magnetosphere, connecting the primary and the companion through two flux tubes (Figure 1). Note that such a closed DC circuit may not always be established (see Section 4). Assuming that it is, the current in the circuit is given by

$$I = \frac{E}{R_{\text{tot}}},$$

where the total resistance of the circuit is

$$R_{\text{tot}} = R_* + R_c + 2R_{\text{mag}},$$

with $R_*$, $R_c$, $R_{\text{mag}}$ the resistances of the magnetic star, the companion, and the magnetosphere, respectively. These resistances depend on the properties of the binary components and
The current in the circuit produces a toroidal magnetic field, which has the same magnitude but opposite directions above and below the equatorial plane. The toroidal field just above the companion star (in the upper flux tube) is \( B_{\phi 1} \simeq -(2\pi/c)J_f \), where \( J_f \sim -\dot{T}/R_c \) is the (height-integrated) surface current. A more precise expression for \( J_f \) can be obtained as follows. The magnetic torque on the companion is

\[
T \simeq -a(\pi R_c^2)J_f B_z/c \simeq \frac{1}{2} a R_c^2 B_z B_{\phi +}.
\]

Comparing this with Equation (5) yields \( J_f \simeq -4\dot{T}/(\pi R_c) \). Thus the azimuthal twist of the flux tube is

\[
\zeta_{\phi} = -\frac{B_{\phi +}}{B_z} = \frac{8\varepsilon}{c R_c R_{tot}|B_z|} = \frac{16v_{rel}}{c^2 R_{tot}},
\]

where \( v_{rel} = a\Delta \Omega = a(\Omega - \Omega_c) \) is the orbital velocity in the corotating frame of the primary star. Clearly, when \( R_{tot} \) is less than \( 16v_{rel}/c^2 \), the flux tube will be highly twisted.

GL already speculated in 1969 that the DC circuit would break down when the twist is too large. (For the Jupiter–Io system parameters adopted by GL, the twist \( |\zeta_{\phi}| \ll 1 \).) Since then, numerous works have confirmed that this is indeed the case. Theoretical studies and numerical simulations, usually carried out in the contexts of solar flares and accretion disks, have shown that as a flux tube is twisted beyond \( \zeta_{\phi} \gtrsim 1 \), the magnetic pressure associated with \( B_{\phi} \) makes the flux tube expand outward and the magnetic fields open up, allowing the system to reach a lower energy state (e.g., Aly 1985; Aly & Kuipers 1990; van Ballegooijen 1994; Lynden-Bell & Boily 1994; Lovelace et al. 1995; Uzdensky et al. 2002). Thus, a DC circuit with \( \zeta_{\phi} \gtrsim 1 \) cannot be realized: The flux tube will break up, disconnecting the linkage between the two binary components.

A binary system with \( R_{tot} \lesssim 16v_{rel}/c^2 \) cannot establish a steady-state DC circuit. The electrodynamics is likely rather complex. Based on the studies of magnetic star–disk systems, where a similar situation occurs (e.g., Aly & Kuipers 1990; Uzdensky et al. 2002), we suggest that a quasi-cyclic circuit may be possible, involving several steps: (1) the magnetic field from the primary penetrates part of the companion, establishing magnetic linkage between the two stars; (2) the linked fields are twisted by differential rotation, generating toroidal field from the linked poloidal field; (3) as the toroidal magnetic field becomes comparable to the poloidal field, the fields inflate and the flux tube breaks, disrupting the magnetic linkage; (4) reconnection between the inflated field lines relaxes the shear and restores the linkage. The whole cycle repeats.

In any case, we can use the dimensionless azimuthal twist \( \zeta_{\phi} \) to parameterize the magnetic torque and energy dissipation rate:

\[
T = \frac{1}{2} a R_c^2 B_z B_{\phi +} = -\zeta_{\phi} \mu^2 R_c^2 /2a^5,
\]

in agreement with Equation (4).

3. MAXIMUM TORQUE AND DISSIPATION

The equations in the previous section clearly show that the binary interaction torque and energy dissipation associated with the DC circuit increase with decreasing total resistance \( R_{tot} \). Is there a problem for the DC model when \( R_{tot} \) is too small? The answer is yes.

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4. OPEN CIRCUIT: ALFVÉN DRAG

As discussed in GL, the validity of the DC circuit model requires that the slippage of the flux tube relative to the companion during the round-trip Alfvén travel time (\(t_A\)) along the flux tube be much less than \(R_c\), i.e., \((\Omega - \Omega_f)\alpha t_A \ll R_c\). When this condition is not satisfied or when the poloidal field opens up due to twist (Section 3), the disturbance generated by the companion’s orbital motion \(v_{rel}\) will propagate along the field line as Alfvén waves and radiate away (Drell et al. 1965). The Alfvén radiation power associated with the “open circuit” is

\[
E_{\text{Alf}} \sim \frac{1}{4\pi}(B_{\phi}v_{rel}/v_A)^2 v_A(2\pi R_c^2) = \frac{1}{2}B_{\phi}^2R_c^2v_{rel}^2/v_A,
\]

where \(v_A\) is the Alfvén speed in the magnetosphere (assuming \(v_{rel} \lesssim v_A\)). The associated drag force is simply \(F_{\phi} = -E_{\text{Alf}}/v_{rel}\), and the torque on the orbit is

\[
T_{\text{Alf}} \sim \frac{1}{2}B_{\phi}^2R_c^2v_{rel}/v_A.
\]

Comparing \(E_{\text{Alf}}\) with Equation (11), we find

\[
\frac{\dot{E}_{\text{Alf}}}{E_{\text{diss}}} \sim \frac{v_{rel}}{\zeta_{\phi}v_A}.
\]

Clearly, \(\dot{E}_{\text{Alf}}\) is always smaller than the maximum \(\dot{E}_{\text{diss}}\) of a DC circuit. Thus, Equation (11) (with \(\zeta_{\phi} \sim 1\)) represents the maximum magnetic dissipation rate of the binary system, regardless of the details of the electrodynamics (e.g., close or open circuit).

5. NEUTRON-STAR–NEUTRON-STAR BINARIES

Gravitational wave (GW) emission drives the orbital decay of the NS binary, with timescale

\[
t_{\text{GW}} = \frac{a}{|\dot{a}|} = \frac{5c^2a^4}{64G^2M_1^2M_2^2q(1+q)} \approx 0.012\left(\frac{a}{30\text{ km}}\right)^4 \text{ s,}
\]

where in the last equality we have adopted \(M_* = 1.4 M_\odot\) and mass ratio \(q = M_1/M_2 = 1\). The magnetic torque tends to spin up the primary when \(\Omega > \Omega_\ast\). Spin–orbit synchronization is possible only if the synchronization time \(t_{\text{syn}} = I_\ast\Omega/[T]\) is less than \(t_{\text{GW}}\) at some orbital radii. With \(I_\ast = \kappa M_\ast R_\ast^2\) and the torque (10), we find

\[
t_{\text{syn}} = \frac{2\kappa(1+q)}{\zeta_{\phi} \Omega} \left(\frac{GM_1^2}{B_{\phi}^2 R_c^2}\right)^2\left(\frac{a}{R_c}\right)^2 
\]

\[
\simeq 2 \times 10^7 \zeta_{\phi}^{-1}\left(\frac{B_\ast}{10^{13}\text{ G}}\right)^{-2}\left(\frac{a}{30\text{ km}}\right)^{7/2} \text{ s,}
\]

where in the second line we have adopted \(\kappa = 0.4\) and \(R_\ast = R_c = 10\text{ km}\). Clearly, even with magnetar-like field strength (\(B_\ast \sim 10^{15}\text{ G}\)) and maximum efficiency (\(\zeta_{\phi} \sim 1\)), spin–orbit synchronization cannot be achieved by magnetic torque. (It was already known that tidal torque, due to both equilibrium tide (Kochanek 1992; Bildsten & Cutler 1992) and resonant tide (Lai 1994; Ho & Lai 1999), cannot synchronize the NS spin during binary inspiral.)

For the same reason, the effect of magnetic torque on the number of GW cycles during binary inspiral, \(N\), is small. We find

\[
\frac{dN}{d\ln f} = \frac{1}{1 + \alpha}\left(\frac{dN}{d\ln f}\right)_0,
\]

where \(f = \Omega/\pi\) is the GW frequency and

\[
\left(\frac{dN}{d\ln f}\right)_0 = \frac{5c^5(1+q)^{1/3}}{96\pi q M_\ast^5(\pi G f)^{5/3}}
\]

is the usual leading-order point-mass GW cycles. The correction factor due to the magnetic torque is

\[
\alpha = \frac{2t_{\text{GW}}}{J_{\text{orb}}/[T]} = \frac{2I_\ast}{\mu_m a^2}\left(\frac{t_{\text{syn}}}{t_{\text{GW}}}\right),
\]

where \(\mu_m = M_*q/(1+q)\) is the reduced mass of the binary. With Equations (15) and (16), we see that GW phase error \(\alpha(dN/d\ln f)_0\) is much less than unity even for \(B_\ast \sim 10^{15}\text{ G}\) and maximum \(\zeta_{\phi} \sim 1\).

The energy dissipation rate is

\[
\dot{E}_{\text{diss}} = \zeta_{\phi}\left(\frac{v_{rel}}{c}\right)^2 \frac{B_{\phi}^2 R_c^6 R_c^2 c}{2a^6}
\]

\[
= 7.4 \times 10^{44}\zeta_{\phi}\left(\frac{B_\ast}{10^{13}\text{ G}}\right)^2\left(\frac{a}{30\text{ km}}\right)^{-13/2} \text{ erg s}^{-1},
\]

where in the second line we have used \(v_{rel} \approx a\Omega\) (for \(\Omega_\ast \ll \Omega\)) and adopted canonical parameters (\(M_\ast = M_\odot\), \(R_\ast = R_c = 10\text{ km}\)). The total energy dissipation per \(\ln a\) is

\[
\frac{dE_{\text{diss}}}{d\ln a} = \dot{E}_{\text{diss}} t_{\text{GW}}
\]

\[
\simeq 8.9 \times 10^{42}\zeta_{\phi}\left(\frac{B_\ast}{10^{13}\text{ G}}\right)^2\left(\frac{a}{30\text{ km}}\right)^{-5/2} \text{ erg.}
\]

Some fraction of this dissipation will emerge as the electromagnetic radiation counterpart of binary inspiral. Whether it is detectable at extragalactic distance depends on the microphysics in the magnetosphere, including particle acceleration and radiation mechanism (e.g., Vietri 1996; Hansen & Lyutikov 2001).

Piro (2012) recently applied the DC circuit model to NS binaries. In the case when the magnetic NS primary dominates the total resistance, he found that the magnetic torque synchronizes the NS spin prior to merger and significantly affects the gravitational wave cycles, even for modest (~10^{12} G) NS magnetic fields. Using the resistance computed by Piro, we find from Equation (9) that the corresponding azimuthal twist \(\zeta_{\phi}\) is much larger (by a factor ~10^{8} at \(\Omega = 100\text{ s}^{-1}\)) than unity, violating the upper limit discussed in Section 3.

If one assumes that the magnetosphere resistance is given by the impedance of free space, \(R_{\text{mag}} = 4\pi/c\), then the corresponding twist is \(\zeta_{\phi} = 2v_{rel}/(\pi c)\), which satisfies our upper limit. The energy dissipation rate is then

\[
\dot{E}_{\text{diss}} = \left(\frac{v_{rel}}{c}\right)^2 \frac{B_{\phi}^2 R_c^6 R_c^2 c}{\pi a^6}
\]

\[
= 1.7 \times 10^{44}\left(\frac{B_\ast}{10^{13}\text{ G}}\right)^2\left(\frac{a}{30\text{ km}}\right)^{-7} \text{ erg s}^{-1}.
\]

Not surprisingly, this is approximately the same as the Alfvén power \(E_{\text{Alf}}\) (see Equation (14)) with \(v_A = c\) and is in agreement with the estimate of Lyutikov (2011).
6. NEUTRON-STAR–BLACK-HOLE BINARIES

The situation is similar to the case of NS–NS binaries. In the membrane paradigm (Thorne et al. 1986), a BH of mass $M_{\text{BH}}$ resembles a sphere of radius $R_{\text{H}} = 2G M_{\text{BH}}/c^2$ (neglecting BH spin) and impedance $R_{\text{H}} = 4\pi/c$. Neglecting the resistances of the magnetosphere and the NS, the azimuthal twist of the flux tube in the DC circuit is

$$\zeta_\phi = \frac{4\nu_{\text{rel}}}{\pi c},$$

which satisfies our upper limit (Section 3). The energy dissipation rate is (cf. Lyutikov 2011; McWilliams & Levin 2011)

$$\dot{E}_{\text{diss}} = \left(\frac{\nu_{\text{rel}}}{c}\right)^2 \frac{2B_0^2 R_0^2 R^2_{\text{H}} c}{\pi a^6} \simeq 5.7 \times 10^{42}\left(\frac{B_0}{10^{13}\text{G}}\right)^2\left(\frac{M_{\text{BH}}}{10M_\odot}\right)^4\left(\frac{a}{3R_{\text{H}}}\right)^7 \text{erg s}^{-1},$$

where we have assumed $M_{\text{BH}}/M_\star \gg 1$.

7. ULTRACOMPACT DOUBLE WHITE DWARF BINARIES

Wu et al. (2002) and Dall’Osso et al. (2006, 2007; see also Wu 2009) developed the DC circuit model for ultracompact double WD binaries, particularly for the systems RX J1914+24 (period $P = 9.5$ minutes) and RX J0806+15 ($P = 5.4$ minutes). Usual mass transfer models appear to have difficulties explaining some of the properties of these systems (e.g., the observed orbital decay). The DC circuit model seeks to account for the observed X-ray luminosity ($10^{35}–10^{36}$ erg s$^{-1}$ for RXJ1914+24 assuming a distance of 100 pc) without mass accretion, while allowing for orbital decay driven by gravitational radiation.

Using Equation (11) with parameters appropriate for compact WD binaries, we find

$$\dot{E}_{\text{diss}} = 3.8 \times 10^{20} \zeta_\phi \left(\frac{\Delta \Omega}{\Omega}\right) \left(\frac{\mu}{10^{32}\text{G cm}^3}\right)^2 \left(\frac{R_\star}{10^4 \text{km}}\right)^2 \times \left(\frac{M_\star + M_\star}{1M_\odot}\right)^{-5/3} \left(\frac{P}{10 \text{ minutes}}\right)^{-13/3} \text{erg s}^{-1}. \tag{25}$$

Note that $\mu = 10^{32}$ G cm$^3$ corresponds to $B_\star \simeq 0.5$ MG (for $R_\star = 6000$ km), approaching the field strengths of intermediate polars. Obviously, even with the maximum asynchronziation ($\Delta \Omega/\Omega = 1$) and maximum efficiency ($\zeta_\phi \sim 1$), $\dot{E}_{\text{diss}}$ falls far short of the observed X-ray luminosities. Wu et al. (2002) calculated the resistance of the WD and used Equation (4) to obtain a much higher energy dissipation power (see their Figure 3)—evidently, their result (which was also adopted by Dall’Osso et al. 2006) corresponds to $\zeta_\phi \gg 1$, violating our upper limit.

8. CLOSE-IN EXOPLANETARY SYSTEMS

Laine & Lin (2012) recently applied the DC circuit model to study the interaction of close-in planets with the magnetosphere of host stars. From their calculation of the resistances of the planet, host star, and magnetosphere, they suggested that magnetic interaction may affect the orbital evolution of close-in super-Earths on a few Myr timescale and produce hot spots on the surface of the host stars (see also Zarka 2007).

Applying Equation (10) to a planetary system ($M_\star = M_\star$, $R_\star = R_\star$), we find that the magnetic torque induces orbital decay (assuming $\Omega > \Omega_\star$, as is the case for close-in planets in a few day orbit) at the rate

$$\frac{d a}{d t} = -\frac{\zeta_\phi \mu^2 R_\star^2}{a^5 M_\star(G M_\star a)^2}. \tag{26}$$

The timescale is

$$a^{1/2} = \frac{5.7 \times 10^{44} \zeta_\phi^{-1} \left(\frac{M_\star}{1M_\odot}\right)^{1/2} \left(\frac{R_\star}{1R_\odot}\right)^{-6} \left(\frac{B_\star}{1\text{G}}\right)^{-2} \times \left(\frac{R_p}{1R_J}\right)^2 \left(\frac{\bar{\rho}_p}{1\text{g cm}^{-3}}\right) \left(\frac{a}{0.04 \text{AU}}\right)^{11/2} \text{yr.} \tag{27}$$

If this energy is accumulated (e.g., building up twist from $\zeta_\phi \sim 0$ to $\zeta_\phi \sim 1$) over time $\Delta t \simeq 2\pi/\Delta \Omega \sim 3$ days and then released suddenly ($\sim \times 10^{26}$ erg for the canonical parameter values adopted in the above equation). This is much smaller than the energy release of solar flares ($10^{32}–10^{35}$ G cm$^3$ s) and of superflares from solar-type stars ($\sim 10^{33}$ erg s; see Maehara et al. 2012).

It is instructive to compare the magnetic torque $T_{\text{mag}} = T$ (Equation (10)) with the tidal torque (due to tide raised on the star by the planet). Parameterizing tidal dissipation by the quality factor $Q_\star$, we have

$$|T_{\text{tide}}| = \left(\frac{9}{4Q_\star}\right) \left(\frac{GM_\star^2 R_\star^5}{a^6}\right), \tag{29}$$

where $Q_\star = 3Q/(2k_2)$ and $k_2$ is the Love number (Goldreich & Soter 1966). Thus,

$$\left|\frac{T_{\text{mag}}}{T_{\text{tide}}}\right| = 3 \times 10^{-12} \zeta_\phi Q_\star \left(\frac{R_\star}{1\text{R}_\odot}\right)^4 \left(\frac{B_\star}{1\text{G}}\right)^2 \times \left(\frac{\bar{\rho}_p}{1\text{g cm}^{-3}}\right)^{-2} \left(\frac{a}{0.04 \text{AU}}\right) \tag{30}$$

With $Q_\star \sim 10^6–10^8$, the magnetic torque generally cannot compete with the tidal torque.

Although we have shown that the orbital motion of a close-in (non-magnetic) planet cannot generate significant dissipation on the surface of a magnetic host star (see Equation (28)), our result does not exclude other possible forms of star–planet
magnetic interactions, such as the intrinsic coronal activity of the star modified by the orbiting planet (e.g., Zarka 2007; Cohen et al. 2011; Lanza 2012). Continued search for the signature of star–planet interaction would be useful (e.g., Shkolnik et al. 2008; Pillitteri et al. 2011; Fares et al. 2012; Miller et al. 2012).

9. CONCLUSION

Closed DC circuit connecting a magnetic primary and a non-magnetic companion (Section 2) can be an efficient unipolar engine in a binary system, potentially more efficient than an “open” circuit engine (see Section 4). The power of this DC engine is inversely proportional to the total resistance $R_{\text{tot}}$ of the circuit. However, we have shown that when $R_{\text{tot}}$ is less than a critical value, $\sim 16 v_{\text{rel}}/c^2$ (in cgs units; see Equation (9)) or $480 (v_{\text{rel}}/c)^2$ Ohms, the magnetic flux tube connecting the two binary components will be highly distorted and the circuit will break. In this case, a quasi-cyclic unipolar engine may operate in the system (Section 3). Thus, there exists an upper limit to the magnetic interaction torque and the associated energy dissipation rate (Equations (10) and (11)) of any unipolar engine in magnetic binaries. Several previous applications of the DC circuit model to different types of binary systems apparently violated this upper limit. We have shown the following.

1. In coalescing double neutron star (NS) or NS–BH binaries. Magnetic interactions cannot synchronize the NS spin with the orbital motion and have a negligible effect on the phase evolution of the gravitational waveform, even for magnetar field strengths. Nevertheless, the energy dissipation associated with the unipolar engine can produce electromagnetic radiation prior to binary merger, although the detectability of this radiation depends on the microphysics of the binary magnetosphere.

2. In ultracompact white dwarf binaries. Magnetic energy dissipation induced by orbital motion is too small to account for the observed X-ray luminosities. Thus, the puzzling behaviors of several sources (RX J1914+24 and RX J0806+15) cannot be explained by the unipolar inductor circuit model.

3. In close-in exoplanetary systems. Interaction between hot Jupiters or super-Earths and the magnetosphere of their host stars does not lead to appreciable orbital evolution, with the possible exception of the early T Tauri phase, when the stellar dipole magnetic field is higher than $10^3$ G. Magnetic energy dissipation induced by the orbital motion of the planet is generally negligible compared to the observed energy releases in stellar flares or superflares.

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