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A neutron star–white dwarf binary model for periodically active fast radio burst sources

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ABSTRACT

We propose a compact binary model with an eccentric orbit to explain periodically active fast radio burst (FRB) sources, where the system consists of a neutron star (NS) with strong dipolar magnetic fields and a magnetic white dwarf (WD). In our model, the WD fills its Roche lobe at periastron, and mass transfer occurs from the WD to the NS around this point. The accreted material may be fragmented into a number of parts, which arrive at the NS at different times. The fragmented magnetized material may trigger magnetic reconnection near the NS surface. The electrons can be accelerated to an ultrarelativistic speed, and therefore the curvature radiation of the electrons can account for the burst activity. In this scenario, the duty cycle of burst activity is related to the orbital period of the binary. We show that such a model may work for duty cycles roughly from 10 min to 2 d. For the recently reported 16.35-d periodicity of FRB 180916.J0158 + 65, our model does not naturally explain such a long duty cycle, since an extremely high eccentricity ($e > 0.95$) is required.

Key words: accretion, accretion discs – binaries: general – stars: neutron – white dwarfs – fast radio bursts.

1 INTRODUCTION

Fast radio bursts (FRBs) are millisecond-duration radio pulses from extragalactic sources, the origin of which remains mysterious (for reviews, see Katz 2018; Cordes & Chatterjee 2019; Petroff, Hessels & Lorimer 2019; Platts et al. 2019). The first FRB was discovered by Lorimer et al. (2007). Recently, the number of detected FRBs has rapidly increased because of the Canadian Hydrogen Intensity Mapping Experiment (CHIME). The first repeating source, FRB 121102, was reported by Spitler et al. (2016), and is also the first FRB that has been localized and associated with a host galaxy (Chatterjee et al. 2017). During the past two years, 19 new repeating FRBs have been discovered (CHIME/FRB Collaboration 2019a,b; Kumar et al. 2019; Fonseca et al. 2020). It remains a controversy whether all FRB sources are repeating ones. The absence of repeating bursts even after hundreds of hours of follow-up and the observed diversity in intrinsic properties (e.g. temporal structure and polarization) of one-off FRBs could be evidence for multiple populations of FRBs (Caleb, Spitler & Stappers 2018). On the other hand, Ravi (2019) suggests that the volumetric rate of one-off FRBs exceeds the rate of all possible cataclysmic FRB progenitors and concludes that most FRB sources are repeating ones.

Most recently, the first example of periodic activity was reported by CHIME/FRB Collaboration (2020), where the source FRB 180916.J0158 + 65 (hereafter FRB 180916) exhibits an activity period of 16.35 d and the bursts arrive in a 4.0-d phase window. FRB 180916 was precisely localized and associated with a star-forming region in a nearby (redshift $z = 0.0337 \pm 0.0002$), nearly face-on, massive spiral galaxy with a total stellar mass of approximately 10^{10} solar masses (Marcote et al. 2020). In addition, no simultaneous event or extended X-ray and gamma-ray emission was detected according to the recent observations of *AGILE* and *Swift* (Tavani et al. 2020), as well as *Chandra* and *Fermi* (Scholz et al. 2020). Obviously, the discovery of periodic activity provides an important clue to reveal the physics of this repeating FRB. Some models have been proposed to interpret the periodic behaviour, such as the precession of a magnetized neutron star (NS) or a magnetar (Levin, Beloborodov & Bransgrove 2020; Tong, Wang & Wang 2020; Yang & Zou 2020; Zanazzi & Lai 2020), the precession of a jet produced by an accretion disc around a massive black hole (Katz 2020), a mild pulsar in a tight O/B-star binary (Lyutikov, Barkov & Giannios 2020), a highly magnetized pulsar whose magnetic field is 'combed' by the strong wind from a companion star (Ioka & Zhang 2020), and a pulsar traveling through an asteroid belt (Dai & Zhong 2020).

In our opinion, even though only one FRB source has well-established periodicity to date, we may expect that there should exist a population of periodically active FRB sources. In this paper, we propose a NS–white dwarf (WD) binary model with an eccentric orbit, where the WD fills its Roche lobe at periastron, to explain the periodic activity of a potential population of FRB sources. The remainder of this paper is organized as follows. The NS–WD binary model is illustrated in Section 2. The relation between the orbital period, the eccentricity, and the WD mass is studied in Section 3. Conclusions and discussion are presented in Section 4.

2 NS–WD BINARY MODEL

In our previous work, Gu et al. (2016) proposed a compact binary model for repeating FRB sources, which consists of a magnetic WD and an NS with strong dipolar magnetic fields. The WD fills its Roche

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lobe, and mass transfer occurs from the WD to the NS through the inner Lagrange point. Magnetic reconnection may be triggered by the accreted magnetized material when it approaches the NS surface, and therefore the electrons can be accelerated to an ultrarelativistic speed. In such a scenario, the characteristic frequency and the time-scale of an FRB can be interpreted by the curvature radiation of the electrons moving along the NS magnetic field lines. By considering the conservation of angular momentum and the gravitational radiation, an intermittent Roche lobe overflow mechanism was proposed for the repeating behaviour of FRB 121102.

According to such a model, the duration of an FRB $t_{\rm w}$ can be estimated by the ratio of the NS radius $R_{\rm NS}$ to the Alfvén speed $v_{\rm A}(= B_{\rm NS}/\sqrt{4\pi\bar{\rho}})$ (Gu et al. 2016):

$$t_{\rm w} = \frac{R_{\rm NS}}{v_{\rm A}} = 1.1 \left(\frac{R_{\rm NS}}{10^6 {\rm cm}}\right) \left(\frac{B_{\rm NS}}{10^{11} {\rm G}}\right)^{-1} \left(\frac{\bar{\rho}}{10^3 {\rm g\,cm^{-3}}}\right)^{\frac{1}{2}} {\rm ms}\,, \quad (1)$$

where $B_{\rm NS}$ is the magnetic flux density of the NS, and $\bar{\rho}$ is the averaged mass density of accreted material. The above equation indicates that strong magnetic fields ($\gtrsim 10^{11}$ G) is a necessary condition for the NS. In addition, a WD is the only possible candidate for the companion in the binary, since the averaged mass density of a non-degenerate star's atmosphere is significantly lower than the required typical value ($10^3\,{\rm g\,cm^{-3}}$) in equation (1). In other words, a binary consisting of an NS and a non-degenerate star is unlikely to account for millisecond-duration bursts.

Bursts from FRB 180916 and some other repeating FRB sources exhibit downward-drifting sub-bursts at a few to tens of MHz ms^{-1} in the CHIME band (CHIME/FRB Collaboration 2019b), and a characteristic drift rate of $\sim$200 MHz ms^{-1} in the 1.1−1.7 GHz band in the case of FRB 121102 (Hessels et al. 2019). According to our model, such a frequency drift may be qualitatively understood as follows. As shown in equation (1) of Gu et al. (2016), the characteristic frequency of the curvature radiation $\nu_{\rm c}$ is proportional to γ^3, where γ is the Lorentz factor of the relativistic electrons. Due to the energy release near the NS surface, the Lorentz factor of electrons may decrease during the radiative processes, which causes that the characteristic frequency drifts lower at later times in the total burst envelope.

In this work, we propose a model following the spirit of Gu et al. (2016) on the radiative mechanism to explain periodically active FRB sources. In contrast to a circular orbit assumption in Gu et al. (2016), we take the eccentricity into account for an NS–WD binary. As illustrated in Fig. 1, the binary orbit is eccentric and the WD fills its Roche lobe at periastron. Around this point, mass transfer occurs from the WD to the NS. The material of the WD can pass through the inner Lagrange point (L_1) and then be accreted by the NS. Similar to Gu et al. (2016), such an accretion process can produce FRBs. For other positions on the eccentric orbit, however, the mass transfer is interrupted since the Roche lobe is not filled by the WD. Thus, according to our model, there exists a window for the bursts in each duty cycle.

We stress that, since the accreted material has angular momentum, viscous processes are necessary to help the material lose angular momentum and eventually fall on to the surface of the NS. During such a process, the accreted material may be fragmented into a number of parts (as shown in Fig. 1), which arrive at the NS at different times. Thus, a mass transfer process around periastron may trigger multiple bursts. In this scenario, the duration of burst activity in each duty cycle is related to the time interval between the arrival time at the NS of the first part of the fragmented material and that of the last one, which can be much longer than the time-scale of the WD passing through periastron. Thus, the activity window for the bursts can occupy a significant phase in each duty cycle, as discovered in FRB 180916.

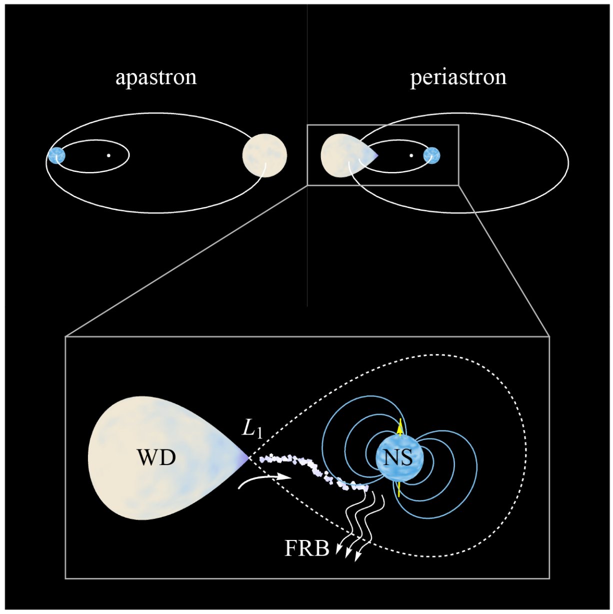

Figure 1. Illustration of the NS–WD binary model with an eccentric orbit, where the WD fills its Roche lobe at periastron. Around periastron, mass transfer occurs from the WD to the NS through the L_1 point. The accretion of fragmented material may trigger multiple bursts.

3 ORBITAL PERIOD

The dynamic equation of the binary (i.e. Kepler's third law) takes the form:

$$\frac{G(M_{\rm NS} + M_{\rm WD})}{a^3} = \frac{4\pi^2}{P_{\rm orb}^2}\,, \quad (2)$$

where $M_{\rm NS}$ and $M_{\rm WD}$ are, respectively, the NS and WD mass, a is the binary separation (major axis of the eccentric orbit), and $P_{\rm orb}$ is the orbital period. The Roche lobe radius $R_{\rm L}$ for the WD at periastron can be expressed as (Eggleton 1983)

$$\frac{R_{\rm L}}{a(1-e)} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1+q^{1/3})}\,, \quad (3)$$

where e is the eccentricity of the orbit, and q is the mass ratio defined as $q \equiv M_{\rm WD}/M_{\rm NS}$. The WD radius $R_{\rm WD}$ is expressed as (Tout et al. 1997)

$$R_{\rm WD} = 0.0115 R_{\odot} \sqrt{(M_{\rm Ch}/M_{\rm WD})^{2/3} - (M_{\rm WD}/M_{\rm Ch})^{2/3}}\,, \quad (4)$$

where $R_{\odot}$ is the solar radius, and $M_{\rm Ch}$ is the Chandrasekhar mass limit, $M_{\rm Ch} = 1.44\,M_{\odot}$.

Based on the assumption that the WD fills its Roche lobe at periastron, i.e. $R_{\rm WD} = R_{\rm L}$, we can derive the values of $P_{\rm orb}$ by equations (2)–(4) once $M_{\rm NS}$, $M_{\rm WD}$, and e are given. The variation of $P_{\rm orb}$ with $M_{\rm WD}$ for five given eccentricities, e = 0, 0.5, 0.9, 0.95, and 0.99, is shown by the five blue solid curves in Fig. 2, where a typical mass $M_{\rm NS} = 1.4\,M_{\odot}$ is adopted.

The contact NS–WD binaries have been used to explain the ultracompact X-ray binaries (UCXBs; see Nelemans & Jonker 2010). To our knowledge, seven UCXBs of contact NS–WD binaries have well-constrained orbital periods and WD masses: 4U 1543 − 624

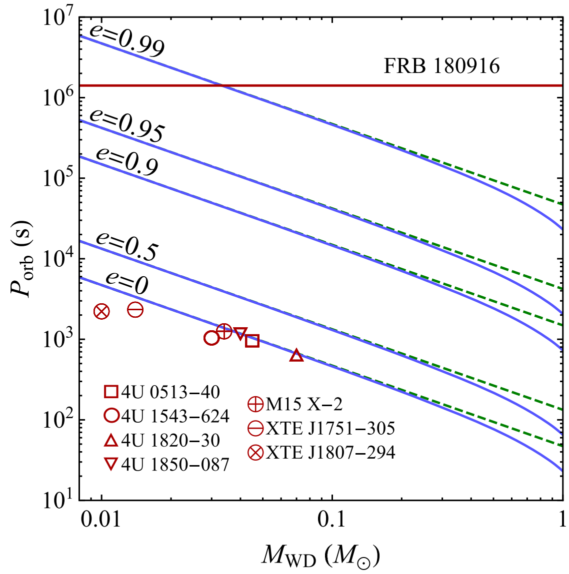

Figure 2. Variation of the orbital period with the WD mass for five given eccentricities, where $M_{\rm NS} = 1.4\,M_\odot$ is adopted. The blue curves correspond to the numerical results calculated using equations (2)–(4), and the green-dashed lines correspond to the analytic relation of equation (7). The horizontal red line represents the reported 16.35-d activity period of FRB 180916. The red symbols denote the seven known UCXBs, which are also contact NS–WD binaries and with well constrained orbital periods and WD masses.

(Wang & Chakrabarty 2004), XTE J1751 − 305 (Gierliński & Poutanen 2005), 4U 1820 − 30 (Güver et al. 2010), XTE J1807 − 294 (Leahy, Morsink & Chou 2011), 4U 1850 − 087, 4U 0513 − 40, and M15 X-2 (Prodan & Murray 2015). In Fig. 2, the red symbols represent the seven known UCXBs, which are well located around the $e = 0$ curve. It is reasonable that their orbits are nearly circular since mass transfer may cause tidal circularization. In addition, it is seen from Fig. 2 that the WD masses of these seven sources are in the range $(\sim 0.01-0.1)\,M_\odot$. Recent hydrodynamic simulations on the contact NS–WD binaries (Bobrick, Davies & Church 2017) showed that only the systems with $M_{\rm WD} < 0.2\,M_\odot$ can exist for a long time, whereas the systems with $M_{\rm WD} > 0.2M_\odot$ experience unstable mass transfer, which leads to tidal disruption of the WD. Thus, a reasonable mass range for the WD in a stable contact NS–WD binary may be $0.01\,M_\odot < M_{\rm WD} < 0.1\,M_\odot$.

On the other hand, the discovered eccentric NS–WD binaries may be classified into two types, i.e. the normal pulsar systems and the millisecond pulsar (MSP) systems. For the former, two systems, PSR J1141 − 6545 and PSR B2303 + 46, have been discovered in our Galaxy (e.g. Kalogera et al. 2005; Sravan et al. 2014). PSR J1141 − 6545 has an eccentricity $e = 0.17$ and a orbital period $P_{\rm orb} = 4.744$ h, and PSR B2303 + 46 has $e = 0.658$ and $P_{\rm orb} = 296.2$ h. The relatively long orbital periods indicate that these two systems are detached binaries. For the MSP systems, four sources have been discovered (e.g. Barr et al. 2017): PSR J2234 + 0611, PSR J1950 + 2414, PSR J0955 − 6150, and PSR J1946 + 3417. The four systems exhibit similar properties: the eccentricity $e \approx 0.08-0.14$ and the orbital period $P_{\rm orb} = 22-32$ d. The long orbital periods also imply that these systems are detached binaries. Referring to the above discovered eccentric NS–WD binaries, a reasonable range for the eccentricity may be $0 < e < 0.9$.

With a pair of reasonable ranges $0.01M_\odot < M_{\rm WD} < 0.1M_\odot$ and $0 < e < 0.9$, we obtain the range of $P_{\rm orb}$ roughly from 10 min to 2 d, as shown in Fig. 2. In other words, our compact binary model may work for the duty cycle of burst activity from 10 min to 2 d. We should note that the eccentricity is not with equal probability within the range $0 < e < 0.9$. According to the discovered eccentric NS–WD systems, we may expect that most eccentric NS–WD binaries have relatively low eccentricities ($e \lesssim 0.1$), and a small fraction of NS–WD binaries may have moderate or high values ($e > 0.1$). Thus, if our mechanism can work for a certain potential population of repeating FRB sources, then the duty cycles of most sources should exist in the range roughly from 10 min to 2 h (corresponding to $e \lesssim 0.1$).

The horizontal red solid line in Fig. 2 represents the reported 16.35-d activity period of FRB 180916, which is far beyond the above range of $P_{\rm orb}$. The red solid line in Fig. 2 indicates that an extremely high eccentricity ($e > 0.95$) is required according to our model. Thus, our model does not naturally explain such a long duty cycle.

In addition, we may derive a simple analytic relation between $P_{\rm orb}$, $M_{\rm WD}$, and e as follows. The Roche lobe radius $R_{\rm L}$ takes the following simple form (Paczyński 1971) instead of equation (3):

$$\frac{R_{\rm L}}{a(1-e)} = 0.462\left(\frac{M_{\rm WD}}{M_{\rm NS}+M_{\rm WD}}\right)^{1/3}, \tag{5}$$

and equation (4) may be simplified as

$$R_{\rm WD} = 0.0115 R_\odot (M_{\rm CH}/M_{\rm WD})^{1/3}. \tag{6}$$

Thus, we derive the following analytic relation:

$$P_{\rm orb} = 471\left(\frac{M_{\rm WD}}{0.1M_\odot}\right)^{-1}(1-e)^{-\frac{3}{2}}\ {\rm s}. \tag{7}$$

Such a simple relation is independent of $M_{\rm NS}$. The analytic relation is plotted in Fig. 2 by the five green-dashed lines. It is seen that, for the relatively low WD mass region ($0.01M_\odot < M_{\rm WD} < 0.1M_\odot$), the analytic relation is in good agreement with the numerical results calculated using equations (2)–(4).

4 CONCLUSIONS AND DISCUSSION

In this paper, we have proposed an NS–WD binary model with an eccentric orbit for periodically active FRB sources. The WD fills its Roche lobe at periastron and mass transfer occurs around this point. The curvature radiation of the ultrarelativistic electrons, which have been accelerated by the magnetic reconnection, can account for the burst activity. In this scenario, the duty cycle of the burst activity is related to the orbital period of the binary. Based on a pair of reasonable ranges for the eccentricity and the WD mass, i.e. $0 < e < 0.9$ and $0.01\,M_\odot < M_{\rm WD} < 0.1\,M_\odot$, we have shown that our model may work for the duty cycle roughly from 10 min to 2 d. For the unique known source with periodic activity, FRB 180916, our model does not naturally explain such a long duty cycle since an extremely high eccentricity ($e > 0.95$) is required.

As discussed in CHIME/FRB Collaboration (2020), one possible explanation for the discovered 16.35-d periodicity is orbital motion, with either a stellar or compact-object companion. The model of a mildly powerful pulsar in a tight O/B-star binary (Lyutikov et al. 2020) hypothesizes that the observed periodicity is due to absorption of the FRB pulses in the O/B star's wind. Such a system has a relatively long orbital period (> a few days), so it is applicable to long duty cycles, such as the 16.35-d periodicity. On the contrary, our model of the NS–WD binary suggests that the observed periodicity is related to the mass transfer process around periastron, which is likely to account for relatively short duty cycles, i.e. less than 2 d

($e < 0.9$). We should stress that, if most repeating FRB sources are found to have long duty cycles of burst activity (> a few days), then our model will be ruled out.

An open question is on what time-scale the orbit can be circularized to a lower eccentricity due to the accretion around periastron. Sepinsky et al. (2009) studied the orbital evolution due to mass transfer in eccentric binaries, by considering the effects of mass and angular momentum loss from the system. They found that, when systemic mass and angular momentum loss are taken into account, the usually adopted assumption of rapid orbital circularization during the early stages of mass transfer remains unjustified. According to their results, the orbital semimajor axis and eccentricity can either increase or decrease, which is related to the rates of systemic mass and angular momentum loss. They applied the results to explain the observation of non-zero orbital eccentricities in mass-transferring binaries, such as a well-known NS X-ray binary, Circinus X-1, with a 16.6-d orbital period and a high eccentricity ($e \sim 0.7-0.9$; Johnston, Fender & Wu 1999) or a moderate eccentricity ($e \sim 0.4$; Johnston, Soria & Gibson 2016). Apart from the accretion process around periastron, gravitational radiation may also play an important role in the orbital circularization in close binaries. The issue of the orbital circularization is beyond the scope of this paper, and is worth studying in future works.

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DATA AVAILABILITY

No new data were generated or analysed in support of this research.

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