A Neutron Star-White Dwarf Binary Model for Periodic Fast Radio Bursts

Wei-Min Gu,1 Tuan Yi,1 and Tong Liu1

1Department of Astronomy, Xiamen University, Xiamen, Fujian 361005, P. R. China

ABSTRACT

We propose a neutron star-white dwarf (NS-WD) binary model with an elliptical orbit to explain the periodic activity of repeating fast radio bursts (FRBs). The WD fills its Roche lobe at the pericenter, and the mass transfer may occur from the WD to the NS around this point, resulting in multiple bursts. In this scenario, the activity period is identical to the orbital period of the binary. We show that such a model may work well for the period roughly from ten minutes to two days. In order to interpret the recently reported 16.35-day periodicity of FRB 180916.J0158+65, an extremely high eccentricity ($e > 0.95$) is required according to our model.

Keywords: accretion, accretion disks — binaries: general — neutron stars — white dwarfs

1. INTRODUCTION

Fast radio bursts (FRBs) are millisecond-duration radio pulses from extragalactic sources, the origin of which remains mysterious (for reviews, see Petroff et al. 2019; Cordes & Chatterjee 2019). The first FRB was discovered by Lorimer et al. (2007). Recently, the number of detected FRBs has fast increased, which is owing to the powerful detector, the Canadian Hydrogen Intensity Mapping Experiment (CHIME). The first repeating source, FRB 121102, was reported by Spitler et al. (2016), which is also the first FRB that has been localised and associated with a host galaxy (Chatterjee et al. 2017). In 2019, eight repeating FRBs were discovered by the CHIME/FRB collaboration (CHIME/FRB Collaboration et al. 2019).

Most recently, the first periodic activity was reported by The CHIME/FRB Collaboration et al. (2020), where the source FRB 180916.J0158+65 (hereafter FRB 180916) exhibits an activity period of 16.35 days and the bursts arrive in a 4.0-day phase window. Obviously, such a discovery provides an important clue to reveal the physics of this repeating FRB. Some models have been proposed to interpret the periodic behavior, such as the precession mechanism of a magnetized neutron star or a magnetar (Yang & Zou 2020; Levin et al. 2020; Zanazzi & Lai 2020), a mild pulsar in tight O/B-star binary (Lyutikov et al. 2020), and a binary comb model (Ioka & Zhang 2020).

In this Letter, we propose a neutron star-white dwarf (NS-WD) binary model with an elliptical orbit, where the WD fills its Roche lobe at the pericenter, to explain the periodic behavior of FRBs. The remainder of this Letter is organized as follows. The NS-WD binary model is illustrated in Section 2. The relation among 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 consisting of a magnetic WD and an NS with strong bipolar magnetic fields. The WD fills its Roche 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 materials when they approach the NS surface, and therefore the electrons can be accelerated to an ultra-relativistic speed. In such a scenario, the characteristic frequency and the timescale 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 behavior of FRB 121102.
In the present work, we focus on the periodicity of repeating FRBs. In our model, the radiative mechanism follows the spirit of Gu et al. (2016). Different from a circular orbit assumption in Gu et al. (2016), we take the eccentricity into account for an NS-WD binary. As illustrated in Figure 1, the binary orbit is elliptical and the WD fills its Roche lobe at the pericenter. Around this point, mass transfer may occur from the WD to the NS. The materials 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 elliptical orbit, however, there is no burst since the Roche lobe is not filled by the WD and therefore the mass transfer is interrupted. Thus, according to our model, there exists a window for the bursts in each cycle.

We would stress that, since the accreted materials have angular momentum, the viscous process is necessary to help most of the materials lose their angular momentum and eventually fall onto the NS. During such a process, the accreted materials may be fragmented into a number of parts (as shown in Figure 1), which arrive at the NS at different time. Thus, a mass transfer process around the pericenter may trigger multiple bursts. The timescale of the window for bursts can be much longer than that of the WD passing through the pericenter.

3. ORBITAL PERIOD

The dynamic equation of the binary takes the form:

\[
\frac{G(M_{\text{NS}} + M_{\text{WD}})}{a^3} = \frac{4\pi^2}{P_{\text{orb}}^2},
\]

where \(M_{\text{NS}}\) and \(M_{\text{WD}}\) are respectively the NS and WD mass, \(a\) is the binary separation (major axis of the elliptical orbit), and \(P_{\text{orb}}\) is the orbital period. The Roche-lobe radius \(R_L\) for the WD at the pericenter can be expressed as (Eggleton 1983)

\[
\frac{R_L}{a(1 - e)} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})},
\]

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

\[
R_{\text{WD}} = 0.0115R_\odot (M_{\text{Ch}}/M_{\text{WD}})^{2/3} - (M_{\text{WD}}/M_{\text{Ch}})^{2/3},
\]

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

Based on the assumption that the WD fills its Roche lobe at the pericenter, i.e. \(R_{\text{WD}} = R_L\), we can derive the values of \(P_{\text{orb}}\) by Equations (1-3) once \(M_{\text{NS}}\), \(M_{\text{WD}}\) and \(e\) are given. The variation of \(P_{\text{orb}}\) with \(M_{\text{WD}}\) for five given eccentricities, \(e = 0, 0.5, 0.9, 0.95\) and 0.99, is shown by five blue solid curves in Figure 2, where a typical mass \(M_{\text{NS}} = 1.4M_\odot\) is adopted. The seven red symbols represent the seven known ultra-compact X-ray sources, which are also NS-WD binaries: 4U1543-624 (Wang & Chakrabarty 2004), XTE J1751-305 (Paczyński & Poutanen 2005), 4U 1820-30 (Gierliński & Poutanen 2005), XTE J1807-294 (Leahy et al. 2011), 4U1850-087, 4U 0513-40, and M15 X-2 (Prodan & Murray 2015). It is seen that these sources are well located around the \(e = 0\) curve, which implies that their orbits are nearly circular. By assuming a pair of reasonable ranges \(0.01M_\odot < M_{\text{WD}} < 0.1M_\odot\) and \(0 < e < 0.9\), we obtain the range of \(P_{\text{orb}}\) roughly from ten minutes to two days. In other words, our compact binary model may work well for activity periods from ten minutes to two days.

The horizontal red solid line represents the reported 16.35-day activity period of FRB 180916. It is seen from Figure 2 that, in order to interpret such a long period by our model, an extremely high eccentricity \((e > 0.95)\) is required.

In addition, we may derive a simple analytic relation among \(P_{\text{orb}}, M_{\text{WD}},\) and \(e\) as follows. The Roche-lobe radius \(R_L\) takes the following simple form (Paczyński 1971) instead of Equation (2):

\[
\frac{R_L}{a(1 - e)} = 0.462 \left( \frac{M_{\text{WD}}}{M_{\text{NS}} + M_{\text{WD}}} \right)^{1/3},
\]

and Equation (3) may be simplified as

\[
R_{\text{WD}} = 0.0115R_\odot (M_{\text{Ch}}/M_{\text{WD}})^{1/3}.
\]
Thus, we derive the following analytic relation:

\[ P_{\text{orb}} = 471 \left( \frac{M_{\text{WD}}}{0.1 M_\odot} \right)^{-1} (1 - e)^{-\frac{3}{2}} \text{s}. \]  

Interestingly, such a simple relation is independent of \( M_{\text{NS}} \). The analytic relation is plotted in Figure 2 by five green dashed lines. It is seen that, for the relatively low WD mass region (0.01\( M_\odot < M_{\text{WD}} < 0.1 M_\odot \)), the analytic relation is in good agreement with the numerical results calculated by Equations (1-3).

4. CONCLUSIONS AND DISCUSSION

In this Letter we have proposed an NS-WD binary model with an elliptical orbit for the periodic FRBs. The WD fills its Roche lobe at the pericenter, and the mass transfer may occur around this point, resulting in multiple bursts. In the scenario, the orbital period is identical to the activity period of the repeating FRB. Based on the relation among the orbital period \( P_{\text{orb}} \), the eccentricity \( e \), and the WD mass \( M_{\text{WD}} \), we have shown that our model may work well for the period roughly from 10 minutes to two days. For the unique known source with periodic activity, FRB 180916, the period of 16.35 days is significantly beyond the above range. In order to explain such a long period, an extremely high eccentricity (\( e > 0.95 \)) is required according to our model.

As mentioned in Section 1, nine repeating FRBs have been detected since the discovery of the first repeating source, FRB 121102. However, up to date, FRB 180916 is the only source which has been reported to have periodic activity. Does this source have different origin from the other repeaters? In our opinion, many repeating FRBs may have periodic behavior, but the periodicity may not be easy to be revealed. There are two timescales: one is the timescale of the periodicity, the other is the timescale of the activity window. Taking our model as an example, the former timescale is the orbital period \( P_{\text{orb}} \), and the latter timescale is related to the different arrival time for the fragmented materials onto the NS (denoted as \( T_{\text{frag}} \)), as mentioned in the last paragraph of Section 2. For the cases with \( P_{\text{orb}} \gg T_{\text{frag}} \), the periodicity is not difficult to be discovered, since \( T_{\text{frag}} \) works as a relatively narrow window in each period. On the contrary, for the cases with \( P_{\text{orb}} \ll T_{\text{frag}} \) (such as low eccentricity in our model), the existent periodicity may be shaded by the continuous activity. In this spirit, it seems understandable why the first discovered periodicity is quite a long period of more than two weeks.

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Figure 1. Illustration of the NS-WD binary model with an elliptical orbit, where the WD fills its Roche lobe at the pericenter. Around the pericenter, mass transfer may occur from the WD to the NS through the $L_1$ point. The accretion of fragmented materials may trigger multiple bursts.
Figure 2. Variation of the orbit period with the WD mass for five given eccentricities, where $M_{NS} = 1.4M_\odot$ is adopted. The blue curves correspond to the numerical results calculated by Equations (1-3), and the green dashed lines correspond to the analytic relation of Equation (6). The horizontal red line represents the reported 16.35-day activity period of FRB 180916. The red symbols denote seven known ultra-compact X-ray sources, which are also NS-WD binaries.