Postprint: Revisiting the Binary Model for Periodic Repeating Fast Radio Bursts

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Abstract

Building upon the compact binary model with elliptical orbits as the origin of periodically repeating Fast Radio Bursts (FRBs), we consider the influence of gravitational radiation on the periodic behavior of FRBs. This binary system comprises a neutron star with a strong dipole magnetic field and a magnetized white dwarf. When the white dwarf fills its Roche lobe, material is transferred to the surface of the neutron star through the inner Lagrangian point. Due to conservation of angular momentum, the white dwarf may be displaced from the Roche lobe after an outburst, and subsequently, during its evolution, fill its Roche lobe again due to gravitational radiation, thereby realizing a subsequent outburst. In this scenario, the period of FRBs corresponds to the binary orbital period Porb, and the relationship between it and the time interval Δt between two mass transfer events is the key factor determining whether periodic behavior can manifest. Evidently, Δt   Porb or Δt < Porb are necessary conditions for the manifestation of periodic behavior. Conversely, if Δt » Porb, the periodicity will be difficult to observe. The results indicate that only FRBs with relatively long periods can exhibit periodic behavior, which suggests that it is reasonable that the only two periodic FRBs currently known both correspond to long periods.

Full Text

Revisiting the Binary Model for Periodically Repeating Fast Radio Bursts

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Abstract: Fast Radio Bursts (FRBs) are transient radio pulses of cosmological origin, which have two types: repeating FRBs and non-repeating FRBs. Building upon the eccentric compact binary model as the origin of periodically repeating FRBs, we consider the effects of gravitational-wave (GW) radiation on the periodic activity of repeating FRBs. The compact binary system composed of a neutron star (NS) with a strong bipolar magnetic field and a magnetic white dwarf (WD) may be able to explain the repeated behavior of repeating FRBs. When the WD fills its Roche lobe, mass transfer will occur through the inner Lagrange point to the surface of the NS. After an explosion, the WD may be kicked away owing to the conservation of angular momentum, and refills its Roche lobe at the next periastron, due to the decrease of orbital separation through GW radiation to realize another. In this scenario, the period of the repeating FRBs should be equivalent to the orbital period P_{orb}. Thus, the relationship between P_{orb} and the time interval of two adjacent mass-transfer processes Δt is a key factor that may determine whether the periodic activity can show up. Obviously, $\Delta t \approx P_{\mathrm{orb}}$ or $\Delta t < P_{\mathrm{orb}}$ is a necessary condition for the periodic activity to appear. On the contrary, for $\Delta t \gg P_{\mathrm{orb}}$, the periodicity will be hard to discover. The results show that the periodic activity is more likely to show up for relatively long periods, which may be the reason that only two sources having been claimed to have periodic activity, both correspond to relatively long periods.

Keywords: Fast Radio Burst; white dwarf; neutron star; gravitational radiation; compact binary stars

Introduction

Fast Radio Bursts (FRBs) are mysterious radio explosion phenomena first detected in 2007. Due to low signal-to-noise ratio, the first FRB was once thought to be possible interference from artificial signals. However, subsequent discoveries of more FRBs have made FRB research a new important frontier in high-energy astrophysics and time-domain astronomy. The physical origin of FRBs remains a mystery. Currently detected FRBs are of two types: repeating and non-repeating, and whether they share the same physical origin is also an open question [2].

The Canadian Hydrogen Intensity Mapping Experiment (CHIME), a radio telescope operating in the 400–800 MHz band with a large collecting area, huge field of view, and powerful correlator, has greatly increased the FRB sample. CHIME detected FRB 180916, which exhibits periodic activity [3], sparking intense research interest in the physical origin of periodic FRBs. So far, only two sources—FRB 180916 and FRB 121102—have shown periodic behavior, with FRB 180916 displaying a possible 16.35-day period and an active window of approximately 4 days [3], while FRB 121102 shows a possible 157-day period. However, not all predicted active windows for these sources have observed bursts.

Current models explaining periodic FRB activity mainly include: (1) FRBs occurring in binary systems containing a compact stellar object (such as a neutron star or black hole), where the FRB period corresponds to the binary orbital period [4–5]; (2) an extremely slowly rotating neutron star causing an ultra-long spin period of the burst source [6]; and (3) FRBs originating from persistent radiation regions in neutron star magnetospheres [7].

The Neutron Star–White Dwarf Binary Model

Based on the neutron star–white dwarf binary model with elliptical orbits, we investigate the influence of gravitational radiation on FRB periodic behavior. This model uses a compact binary system with an elliptical orbit to explain the periodic activity of repeating FRBs [4]. The system consists of a magnetized white dwarf and a neutron star with a strong dipole magnetic field. When the white dwarf fills its Roche lobe at periastron, mass transfer occurs through the inner Lagrange point to the neutron star surface. At other orbital positions, the Roche lobe is not filled, preventing mass transfer.

The accreted material may be torn into a series of fragments under viscous effects, which reach the neutron star surface at different times along magnetic field lines, forming multiple FRB bursts through curvature radiation. The period of these burst events should equal the orbital period P_{orb}. The semi-major axis of the elliptical orbit is denoted by a.

According to angular momentum conservation, after a mass transfer event, the white dwarf may be kicked away. Due to gravitational radiation, the orbital separation decreases until the white dwarf refills its Roche lobe, triggering the next mass transfer [9–10]. The time interval t between adjacent bursts is a crucial timescale that determines whether periodic behavior can be observed.

Gravitational Radiation Effects on Orbital Evolution

The orbital angular momentum J of the binary system is given by $J = M$. Assuming a transferred mass e (where e is the eccentricity), when the white dwarf fills its Roche lobe, mass transfer from the white dwarf to the neutron star occurs. The change in orbital angular momentum can be expressed as $J = \lambda$, where λ is a parameter representing orbital angular momentum loss due to outflow.

The orbital angular velocity is $\Omega = G$, and the distance between the neutron star and the Lagrangian point is $= qa/$, which has the form $0.227 \log$. In our model, mass transfer occurs when the white dwarf fills its Roche lobe at periastron and is accreted by the neutron star. The separation a between the two stars changes accordingly.

The change in binary separation due to mass variation can be derived from equations (1)–(3): $-q - \lambda$. After a mass transfer event, the separation evolves with time as [11] until gravitational radiation causes the next mass transfer.

The relationship caused by gravitational radiation is $= -64$, with $e^2 + 37$ and $[0.5(10.227(1) \log e^2 + 37$.

Selecting typical neutron star mass $M_1 = 1.4M_\odot$, we can obtain the time interval between two adjacent bursts. Based on the elliptical orbit binary model for periodically repeating FRBs, we consider the effects of gravitational radiation on periodic observational results.

Parameter Constraints and Observable Periodicity

In this model, for given masses M, the period should equal the orbital period P_{orb}. We can obtain the binary orbital period P_{orb} from equation (6), where λ represents the parameter for orbital angular momentum loss due to outflow. There are two limiting cases: if accreted material does not carry orbital angular momentum, or if it carries Keplerian angular momentum at the Lagrange point.

Figure 1 shows the ratio of time interval to orbital period $\Delta t/P_{\mathrm{orb}}$ as a function of λ for different eccentricities ($e = 0, 0.5, 0.9$) with $M_2 = 0.1M_\odot$. For circular orbits, $\Delta t/P_{\mathrm{orb}}$ decreases with increasing λ when λ is large, while for elliptical orbits, $\Delta t/P_{\mathrm{orb}}$ hardly changes with λ. We select $\lambda = 0.5$ in our analysis.

For compact NS–WD binaries, after transferring a certain mass, the white dwarf is kicked away. Gravitational radiation causes orbital decay, initiating the next mass transfer. Figure 1 gives the time interval between two adjacent bursts. Dynamical simulations show that WD–NS systems experience unstable mass transfer only when $M_2 < 0.2M_\odot$ [12], leading to tidal disruption of the white dwarf. Reasonable white dwarf masses are low [4], likely in the range $0.01 < M_2/M_\odot < 0.1$ for ultra-compact X-ray binaries (UCXBs) [9].

Dependence on Eccentricity and Mass

Figure 2 shows the relationship between Δt and P_{orb} as a function of eccentricity for three mass transfers ($\Delta M = 10^{-11}M_\odot$ and $10^{-10}M_\odot$) and two white dwarf masses ($M_2 = 0.05M_\odot$ and $0.1M_\odot$). Arrows indicate increasing eccentricity direction; vertical dashed lines mark the reported period position for FRB 180916; dotted lines show the critical relation $\Delta t = P_{\mathrm{orb}}$.

When the white dwarf mass is small ($M_2 = 0.05M_\odot$), almost all time intervals are much larger than the orbital period, making periodic behavior unobservable. For larger white dwarf masses ($M_2 = 0.1M_\odot$), there exist time intervals where $\Delta t \approx P_{\mathrm{orb}}$ or Δt is slightly greater than P_{orb}, allowing observable periodic behavior. However, this only occurs at relatively large P_{orb} values.

Figure 3 more specifically shows eccentricity's effect, plotting $\Delta t/P_{\mathrm{orb}}$ versus eccentricity for $M_2 = 0.1M_\odot$ and transferred masses of $10^{-11}M_\odot$ and $10^{-10}M_\odot$. The horizontal dashed line indicates the critical relation $\Delta t/P_{\mathrm{orb}} = 1$. We see that only when eccentricity is relatively large ($e > 0.9$) does $\Delta t/P_{\mathrm{orb}}$ approach or fall below 1, meaning periodic behavior of repeating FRBs can only be observed for high eccentricities under current parameters.

Conclusion

Fast Radio Bursts are mysterious radio explosion phenomena. Researchers have found only two repeating FRBs (FRB 180916 and FRB 121102) that exhibit periodic behavior. Circular-orbit compact binary models may explain this periodicity. The binary system contains a magnetized white dwarf and a neutron star with a strong dipole magnetic field. When the white dwarf fills its Roche lobe, material transfers to the neutron star surface. The accreted material may fragment, reaching the neutron star surface at different times. Due to angular momentum conservation, the white dwarf may be kicked away after an outburst, then refill its Roche lobe via gravitational radiation to trigger another burst. In this scenario, the repeating FRB period corresponds to the binary orbital period.

Our focus is on how gravitational radiation affects FRB periodicity in the elliptical-orbit compact binary model. We find that whether outflow material carries angular momentum affects circular orbits somewhat but has little effect on elliptical orbit calculations. Using this model to explain FRB periodicity requires relatively high eccentricities. For such systems, we can observe periodic behavior when the orbital period reaches or is slightly greater than the time interval, but not all periods are active.

We find that for small white dwarf masses, time intervals far exceed orbital periods, preventing observable periodicity. Only for relatively massive white dwarfs do time intervals approach orbital periods, allowing periodic FRB behavior. However, not all periods are active—this only occurs at relatively large orbital periods. This conclusion matches observations of FRB 180916 and FRB 121102, showing it is reasonable that only two long-period FRBs display periodicity and that not all active windows detect bursts.

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Figure Captions:

[Figure 1: see original paper] Ratio of the time interval $\Delta t/P_{\text{orb}}$ to the orbital period as the function of λ for different eccentricities $e = 0, 0.5, 0.9$, with $M_2 = 0.1M_{\odot}$ and $e = 0.99$.

[Figure 2: see original paper] The relationship between the time interval Δt and the orbital period P_{orb} as it varies with eccentricities $e = 0.1 - 0.999$, for three mass transfers $\Delta M = 10^{-11}M_{\odot}$ and $10^{-10}M_{\odot}$, and two WD masses $M_2 = 0.05M_{\odot}$ and $0.1M_{\odot}$. The shear heads show the direction of increasing eccentricity. The vertical dashed lines report the position of the period for FRB 180916, and the dotted lines show the critical relation $\Delta t = P_{\text{orb}}$.

[Figure 3: see original paper] Ratio of the time interval $\Delta t/P_{\text{orb}}$ as the function of eccentricity e for $M_2 = 0.1M_{\odot}$. The horizontal dashed line shows the critical relation $\Delta t/P_{\text{orb}} = 1$.

Note: Figure translations are in progress. See original paper for figures.