A Circumbinary Disk Scenario for the Negative Orbital-period Derivative of the Ultra-compact X-Ray Binary 4U 1820-303

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Abstract

It is generally thought that an ultra-compact X-ray Binary is composed of a neutron star and a helium white dwarf donor star. As one of the most compact binaries, 4U 1820-303 in globular cluster NGC 6624 was predicted to have an orbital period of $P/P \approx 1.1 \times 10^{-7}$ yr$^{-1}$ if the mass transfer is fully driven by gravitational radiation. However, recent analysis of 16 year data from Rossi X-ray Timing Explorer and other historical records has yielded a negative orbital-period derivative in the past 35 years. In this work, we propose an evolutionary circumbinary (CB) disk model to account for this anomalous orbital-period derivative. 4U 1820-30 is known to undergo superburst events caused by runaway thermal nuclear burning on the neutron star. We assume that, for a small fraction of the superbursts, part of the ejected material may form a CB disk around the binary. If the recurrence time of such superbursts is $\sim$10,000 year and $\sim$10% of the ejected mass feeds a CB disk, the abrupt angular-momentum loss causes a temporary orbital shrink, and the donor’s radius and its Roche lobe radius do not keep in step. Driven by mass transfer and angular-momentum loss, the binary would adjust its orbital parameters to recover a new stable stage. Based on theoretical analysis and numerical simulation, we find that the required feed mass at the CB disk is approximately $\sim 10^{-8} M_\odot$.

Key words: pulsars: individual (4U1820-303) – stars: evolution – X-rays: binaries

1. Introduction

4U 1820−303 (hereafter 4U 1820), located in the globular cluster NGC 6624, is an ultra-compact X-ray binary (UCXB), which is defined by an ultra-short orbital period (usually less than 1 hr). Since its discovery as a bright X-ray source (Giacconi et al. 1974), 4U 1820 has been extensively observed with many X-ray telescopes. Its peak-to-peak modulation period of $\sim 685$ s (Stella et al. 1987; Sansom et al. 1989; Anderson et al. 1997) is generally believed to be the orbital period of a white dwarf orbiting a neutron star (Rappaport et al. 1987).

As the most compact UCXB, the formation and evolution history of 4U 1820 has been widely studied to date. Considering the high stellar density of the globular cluster, Verbunt (1987) suggested that this system was formed via the spiral-in phase of a neutron star into a red giant after their direct collision. Taking common envelope spiral-in into consideration, Bailyn & Grindlay (1987) calculated an evolutionary sequence from 4U 2127+12 in M15 to 4U 1820. In their scenario, the binary system was produced via tidal capture between a main-sequence star and a neutron star. Similarly, Rasio et al. (2000) proposed that this source originated from an exchange interaction between a neutron star and a primordial binary including two main-sequence stars, in which a common envelope evolution phase would subsequently be expected.

Although they adopted two different formation channels for 4U 1820, Verbunt (1987) and Bailyn & Grindlay (1987) agreed that the mass transfer is dominantly driven by gravitational radiation. Based on a similar model, Rappaport et al. (1987) calculated the evolutionary sequence of 4U 1820 and found that its donor star is a helium white dwarf of mass $\sim 0.06 - 0.08 M_\odot$ with a radius within $\sim 20\%$ of a completely degenerate configuration. They also predicted an X-ray luminosity of $L_X \sim 8 \times 10^{37}$ erg s$^{-1}$, and an orbital-period derivation of $\dot{P}/P \sim 1.1 \times 10^{-7}$ yr$^{-1}$ driven by mass transfer from the white dwarf to the neutron star.

However, Sansom et al. (1989) obtained an orbital-period derivative of $\dot{P}/P \sim -6 \times 10^{-8}$ yr$^{-1}$ by Ginga observations. Subsequently, Tan et al. (1991) also reported a negative period derivative at a significance of 99.9%. Employing simultaneous ROSAT/Ginga observations, van der Klis et al. (1993a) reported an average orbital-period derivative $\dot{P}/P \sim (-0.88 \pm 0.16) \times 10^{-7}$ yr$^{-1}$. Based on further observation by ROSAT, van der Klis et al. (1993b) obtained $\dot{P}/P = (-5.3 \pm 1.1) \times 10^{-8}$ yr$^{-1}$. Chou & Grindlay (2001) also reported a negative derivative of $\dot{P}/P \sim -3.5 \times 10^{-8}$ yr$^{-1}$. Recently, Peuten et al. (2014) analyzed the 16 year Rossi X-ray Timing Explorer (RXTE) data of 4U 1820, and refined the negative orbital-period derivative to be $\dot{P}/P = (-5.3 \pm 0.3) \times 10^{-8}$ yr$^{-1}$ at a $>17\sigma$ level. Clearly, all these observations confirmed a negative orbital-period derivative for 4U 1820, which is contrary to the theoretical prediction given by Rappaport et al. (1987). How can we explain the difference in orbital evolution between the binary evolutionary theories and the observations? To resolve this problem, many authors have proposed various scenarios, which can be divided into two categories. In the first one it is thought that the orbital-period derivative arises from binary evolution. Considering the secondary is a non-degenerate helium star of $0.6 M_\odot$ orbiting a $1.3 M_\odot$ neutron star, Savonije et al. (1986) calculated the evolution of a compact binary with an initial period of 37 minutes. They found that the orbital period could be as low as 11 minutes and a negative period derivative could also be attained. Their
calculation indicates that the donor star is a helium-burning star with mass of \( \sim 0.24 M_{\odot} \), which is not expected to exist in old stellar populations like globular clusters (Stella et al. 1987; Verbunt 1987). Assuming that stars more massive than the turn-off mass could be formed during a close encounter in globular clusters, van der Klis et al. (1993a) restudied the possibility of a helium-burning donor star, and obtained a conclusion similar to that of Savonije et al. (1986). Ma & Li (2009) found that a circumbinary disk (CB disk) around the binary could drive low-mass X-ray binaries to periods as short as 6 minutes. Recently, Chen & Podsiadlowski (2016) investigated an alternative formation channel toward UCXBs with an orbital period of 11 minutes, which evolved from intermediate-mass X-ray binaries driven by magnetic braking of Ap/Bp stars. Their simulations also indicate a long-term period-decreasing phase.

In the other case, some researchers have suggested that the apparent orbital-period derivative can be interpreted by an accelerating motion of the binary toward observers. Tan et al. (1991) argued the acceleration may arise from a third body or the cluster potential. Peuten et al. (2014) explored the possibility of a stellar mass remnant close to 4U 1820 or an intermediate-mass black-hole inside NGC 6624, van der Klis et al. (1993b) even suggested that the secular period change was dominated by a systematic or random change of position and shape of an occcluding bulge on the accretion disk rim.

Taking the orbital period change as the result of binary evolution, here we suggest that the negative orbital-period derivative of 4U 1820 could be produced by a temporary CB disk, which can extract orbital angular momentum, via resonant interaction, from the binary system. Our theoretical analysis and numerical simulation indicate that the CB disk mass that can account for the observed orbital-period derivative is approximately \((\sim 1.0-1.5) \times 10^{-8} M_{\odot} \).

In the following section, we present a simple theoretical analysis for the current orbital-period derivative of 4U 1820, and describe the CB disk model in Section 3. The numerical simulation method and simulated results are described in detail in Section 4. In Section 5, we present a brief summary and discussion.

2. Theoretical Analysis of the Current Orbital-period Derivative of 4U 1820

Considering a binary consisting of a neutron star (of mass \( M_1 \)) and a He white dwarf secondary (of mass \( M_2 \)) in a circular orbit, the orbital angular momentum is \( J = 2\pi\mu a^2/P \). Here \( M_1 M_2/(M_1 + M_2) \) is the reduced mass, and \( a \) is the orbital separation. The spin angular momentum of the donor star is neglected because it is much less than the orbital angular momentum. By a simple logarithmic differentiation of the angular momentum, we have

\[
\frac{\dot{P}}{P} = 3 \frac{\dot{J}}{J} + \frac{M_1 + M_2}{M_1 + M_2} - \frac{3 M_1}{M_1} - \frac{3 M_2}{M_2}.
\]

(1)

Taking the Eddington accretion rate \( M_{\text{Edd}} \) into account, the accretion rate of the neutron star is assumed to be \( \dot{M}_1 = \min(f_1|M_2|, M_{\text{Edd}}) \), where \( f_1 \leq 1 \) is a constant. The accretion efficiency of the neutron star is defined as

\[
\beta \equiv \frac{\dot{M}_1}{|M_2|}.
\]

(2)

Therefore, when \( M_{\text{Edd}} < f_1|M_2| \), \( \beta < f_1 \) while \( M_{\text{Edd}} > f_1|M_2| \), \( \beta = f_1 \). X-ray observation performed by Stella et al. (1987) reported an X-ray luminosity of \( 2 \sim 10^{37} \text{erg s}^{-1} \), which implies an accretion rate of \( 4U 1820 \dot{M}_1 \sim 10^{-8} M_{\odot} \text{yr}^{-1} \).

Magnetic braking would stop for a fully convective star (Rappaport et al. 1983; Spruit & Ritter 1983), hence we consider angular momentum loss due to gravitational radiation and mass loss:

\[
\frac{\dot{J}}{J} = \frac{\dot{J}_{\text{GR}}}{J} + \frac{\dot{J}_{\text{ML}}}{J},
\]

(3)

where \( \dot{J}_{\text{GR}} \) and \( \dot{J}_{\text{ML}} \) are the angular-momentum-loss rate by gravitational radiation and mass loss, respectively. The angular-momentum loss rate by gravitational radiation is given by Landau & Lifshitz (1975):

\[
\frac{\dot{J}_{\text{GR}}}{J} = -\frac{32(2\pi)^{3/5}}{5c^{5}} G^{5/3} M_1 M_2 M_T^{-1/3} P^{-8/3},
\]

(4)

where \( c \) is the velocity of light, \( G \) is the gravitational constant, and \( M_T = M_1 + M_2 \) is the total mass of the binary. Taking \( M_1 = 1.58 M_{\odot} \) (Güver et al. 2010), \( M_2 = 0.07 M_{\odot} \), (Rappaport et al. 1987), and \( P_{\text{orb}} = 685 \text{s} \) (Stella et al. 1987; Sansom et al. 1989; Anderson et al. 1997), we can derive \( \dot{J}_{GR}/J \sim 10^{-7} \text{yr}^{-1} \).

The angular-momentum loss rate by mass loss can be written as

\[
\frac{\dot{J}_{\text{ML}}}{J} = 2\pi f_1 (1 - \beta) M_2 a^2 / P,
\]

(5)

where \( f_1 \) is the specific angular momentum of the ejected matter in units of \( 2\pi a^2 P \). In this work, the mass loss during accretion is assumed to form an isotropic wind in the vicinity of the neutron star, and carry away its specific orbital angular momentum, i.e., \( \beta = M_2^2/(M_1 + M_2)^2 \). Based on some parameters mentioned above, one can find \( J_{\text{ML}}/J \sim 10^{-11} \text{yr}^{-1} \). Compared with gravitational radiation, angular-momentum loss due to mass loss can be ignored.

Based on some parameters mentioned above, Equation (1) can yield the current orbital-period derivative of 4U 1820. For a conservative mass transfer, the current period derivative should be \( \dot{P}/P \sim 10^{-7} \text{yr}^{-1} \), and \( \dot{P}/P \sim 5 \times 10^{-7} \text{yr}^{-1} \) for nonconservative mass transfer with \( f_1 = 0.5 \) (Podsiadlowski et al. 2002). Similar to the discussion given by Rappaport et al. (1987), both cases predict a positive orbital-period derivative, which contradicts observation.

3. A CB Disk Model

To interpret the negative orbital-period derivative observed in 4U 1820, here we propose an evolutionary CB disk model. The influence of the CB disk on the evolution of cataclysmic variables (Spruit & Taam 2001; Taam & Spruit 2001), black-hole X-ray binaries (Chen & Li 2006, 2015), Algol binaries (Chen et al. 2006), and UCXBs (Ma & Li 2009) has been studied extensively. All these works show that a CB disk can efficiently extract orbital angular momentum from the binary system, and enhance the mass-transfer rate and accelerate the evolution process. In this work, we adopt a different CB disk model. The resonant interaction between the binary and the CB disk has been well studied (Artymowicz et al. 1991; Lubow & Artymowicz 1996; Lubow & Artymowicz 2000; Dermine et al. 2013), and its predicted orbital angular-momentum loss
rate is given by (Lubow & Artymowicz 1996):
\[
\frac{J_{CB}}{J} = \frac{1}{m} \frac{M_{CB}}{\mu} \left( \frac{H}{R} \right)^2 a \frac{2\pi}{R P}.
\]  
(6)

Here \(M_{CB}\) is the mass of CB disk, \(H\) and \(R\) (= \(\sqrt{r_{in}r_{out}}\), where \(r_{in}\) and \(r_{out}\) are the inner and outer radius of the CB disk, respectively) are the thickness and the half angular momentum radius of the disk, respectively. \(l\) and \(m\) are integers describing the binary potential, \(\alpha (= 0.1)\) is the viscosity parameter of the disk.

Miranda & Lai (2015) studied the tidal truncation between circumstellar and CB disks in binaries, and found that the inner radius of CB disk is \(1.5a < r_{in} < 3.5a\). Following their study, assuming the disk extends from \(r_{in} = 2.5a\) to \(r_{out} = 10a\), the half angular momentum radius of the disk is \(R = 5a\). According to the study of Dullemond et al. (2001), the relative thickness of the CB disk near the inner edge is \(H/R = 0.1-0.25\). Assuming the disk is thin and the non-axisymmetric potential perturbations are small, we take \((H/R)^2 = 1/30\) and \(l = m = 1\) in this work.

According to the above equations, a CB disk with mass of \(~10^{-8}M_{\odot}\) can reproduce the observed negative orbital-period derivative for both the conservative and nonconservative mass transfer cases. The CB disk would certainly slowly induce a small eccentricity (Dermine et al. 2013). However, the tidal interaction between the donor star with a relatively deep convective envelope and the neutron star in such a compact orbit would rapidly circularize the orbit.

We propose that the material of the CB disk comes from some rare superburst events. Superbursts are hour-long thermonuclear runaway burning processes and were first observed by Cornelisse et al. (2000) from the neutron star, low-mass X-ray binary, 4U 1735−444. A superburst of 4U 1820 was discovered by Strohmayer (2000) and Strohmayer & Brown (2002) as the second superburst event ever observed. Subsequently, many other superburst events have been discovered from other LMXBs such as KS 1731−260, Serpens X−1 GX 3+1, and so on. At present, about a dozen superburst sources (candidates) have been reported, and one third of these sources were observed recurrently (Keek et al. 2012). Interestingly, although the recurrence times estimated from observation of other sources are on the order of a year (Kuulkers 2004), the second superburst of 4U1820 was observed to be 11 years after the first event (Keek et al. 2012), which is consistent with the prediction (~13 year) made by Strohmayer & Brown (2002).

Compared with more frequent type I bursts with short durations (typically ~20 s), superbursts release X-ray energy ~10^{42} erg during an event, which is three orders of magnitude higher. Considering a substantial fraction of the released energy during the event is carried away by neutrinos and is conducted to the inner part of the neutron star, the total energy released during the event is much larger >10^{49} erg (Strohmayer & Brown 2002). Observational and theoretical studies indicate that it is a thermonuclear runaway burning process, and the energy source is most likely carbon and/or oxygen on the surface of the neutron star (Strohmayer & Brown 2002; in’t Zand et al. 2012). A detailed analysis indicated the mass of the burning-carbon layer is probably >10^{26} g (Strohmayer & Brown 2002).

In principle, there exists a range for the released energy of different superburst events (Kuulkers et al. 2002). Here, we assume that some peculiar superburst events (with a probability of 0.1%, hereafter rare superbursts) in a layer of ~10^{27} g (5 × 10^{-7} M_{\odot}) may be responsible for the formation and evolution of the CB disk. In our calculation, 20% of the burning-carbon layer was assumed to escape from the neutron star’s surface, and 10% of the ejected material (2% of total burning mass, i.e., \(\Delta M_{CB} = 1.0 \times 10^{-8} M_{\odot}\)) suddenly feeds the CB disk\(^6\) during every rare superburst event. Taking the recurrence time of superburst events of 4U1820 as 10 year, the CB disk would experience a mass feed with \(\Delta M_{CB}\) every ~10,000 year. Meanwhile, the mass of the CB disk is assumed to decrease at a rate of 0.1% \(\dot{M}_{CB}\) yr^{-1} (the CB disk only remains ~5 × 10^{-5} \(\Delta M_{CB}\) at the beginning of the next rare superburst) due to the photo-evaporation of the neutron star’s spin-down energy (Antoniadis 2014). According to Equation (5), the angular-momentum loss due to sudden mass loss from the neutron star’s surface induced by (normal or rare) superburst is ~10^{-10}–10^{-11} J yr^{-1}, and can be disregarded.

4. Numerical Simulation

To evaluate the CB disk scenario in detail, we develop a fast binary-evolution program for 4U 1820. As shown in Figure 1, our calculation starts from a gravitational wave emission dominated, detached binary consisting of a neutron star and a low-mass He white dwarf. To fit the current mass of the neutron star (1.58 M_{\odot}, Güver et al. 2010) and the donor star (0.07 M_{\odot}, Rappaport et al. 1987), the initial input parameters are set to \(M_1 = 1.5 M_{\odot}\), \(M_2 = 0.15 M_{\odot}\), and orbital period \(P = 0.2\) hr. Such an orbital period can ensure the He white

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\(^6\) The viscous timescale of a typical CB disk is of the order of years, much shorter than the evolutionary timescale considered here.
dwarf decouples from its Roche lobe, and the steady mass-transfer condition is not introduced manually but satisfied via slowly adjusting the gravitational wave emission. This is different from Rappaport et al. (1987) where the evolution was studied from a Roche lobe filled binary, with a simple relation between the mass of white dwarf donor and the orbital period, \( P \propto M_d^{-1} \).

Once the donor star overflows its Roche lobe due to gravitation radiation, it transfers matter to the neutron star at a rate (Nelson & Eggleton 2001):

\[
M_2 = -f_2 \log^3 \left( \frac{R_2}{R_L} \right),
\]

where \( f_2 \) is a constant factor. In calculation, we take \( f_2 = 5 \times 10^{-3} M_\odot \text{yr}^{-1} \). \( R_2 \) is the radius of the secondary, and \( R_L = qf(q) \) is the Roche lobe radius of the donor star. The function \( f(q) \) only relates to the mass ratio \( q = M_2/M_1 \). In this paper, we adopt the approximate description given by Eggleton (1983), i.e.,

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

Utilizing a simple polytropic index \( n = 3/2 \), the donor star’s radius is given by (Chandrasekar 1939)

\[
R_2 = 0.0128(1 + X)^{5/3} f_3 \left( \frac{M_2}{M_\odot} \right)^{-1/3} R_\odot,
\]

where \( X \) is the mass abundance of hydrogen (\( X = 0 \) for a pure helium white dwarf in this paper), and \( f_3 \geq 1 \) (\( f_3 = 1 \) in this paper) is the radius ratio between a donor star and a white dwarf with the same mass, which is completely degenerate and only supported by the Fermi pressure of the electrons.

To test the influence of input parameters on the evolution and compare the results with other works, we ran four different models as follows:

1. Model 1: \( f_1 = 1.0, \Delta M_{\text{CB}} = 0 \);
2. Model 2: \( f_1 = 1.0, \Delta M_{\text{CB}} = 1 \times 10^{-8} M_\odot \);
3. Model 3: \( f_1 = 0.5, \Delta M_{\text{CB}} = 0 \);
4. Model 4: \( f_1 = 0.5, \Delta M_{\text{CB}} = 1 \times 10^{-8} M_\odot \).

Figure 2 shows the evolution of a UCXB under different models in the \( P-M_2 \) plane. It is clear that the orbital-period evolution can be divided into two stages. In the first stage, gravitational radiation dominates the angular momentum loss of the binary, and causes the orbit to sharply shrink. After the donor star overflows its Roche lobe, the orbital decay becomes slower because the material is transferred from the less massive donor star to the more massive accretor. Subsequently, the orbital period gradually increases, and the second stage starts where the evolution roughly obeys an orbital-period–donor mass relation of \( P \propto M_2^{-1} \). Our simulation also shows that at an orbital period of \( \sim 11 \) minutes, the donor star mass is in the range of \( \sim 0.06–0.07 \) \( M_\odot \), in good agreement with the predication by Rappaport et al. (1987). The CB disk formed by the first rare superburst is assumed to experience a mass feed if the mass-transfer rate \( M_2 > 1.0 \times 10^{-8} M_\odot \text{yr}^{-1} \). It seems that the four models have similar evolutionary tracks. However, in the inset of Figure 2, models 2 and 4 predict short-term orbital-decay episodes that are induced by sudden mass feed of the CB disk.

To interpret the short-term orbital-decay episodes in detail, the evolutions of angular-momentum loss rate induced by gravitational radiation and the CB disk for Model 2 are shown in the left panel of Figure 3. Compared with the continuous evolution of \( J_{\text{GR}}/J \), the sudden mass feedings at CB disk induce sharp dips of \( J_{\text{CB}}/J \). As shown in the right panel of Figure 3, for Model 2, the sudden increase of angular-momentum loss rate induces the sudden decrease of Roche lobe radius of the donor star. Since the radius of the white dwarf increases gradually due to mass loss, the stable mass-transfer condition \( R_f/R_e = R_L/R_L \) (Di Salvo et al. 2008) is ruined. With the mass decay of CB disk, the angular-momentum loss rate gradually decreases, and the stable mass-transfer condition is re-established again before next mass feeding.

In Figure 4, we summarize the evolution of the donor mass, the mass-transfer rate, the orbital period, and the orbital-period derivative. Some key results can be summarized as follows:

1. Our calculations show that, after each mass feed of rare superburst there exists a short-term orbital-period decrease phase for 900 years for Models 2 and 4. Roughly speaking there is a 9% probability to see 4U1820 in orbital decay.
2. After the recovery of a stable mass transfer, both Models 2 and 4 yield a higher orbital-period derivative than Models 1 and 3. This discrepancy originates from additional mass loss relating to the formation of a CB disk.
3. A CB disk can efficiently extract the orbital angular momentum from the binary, accelerate the evolutionary process, and result in a smaller donor mass and a higher mass-transfer rate.
4. The current mass-transfer rate of the donor star is \( \sim 1.1–1.2 \times 10^{-8} M_\odot \text{yr}^{-1} \). This indicates an X-ray luminosity of \( \sim 5–12 \times 10^{37} \text{ erg s}^{-1} \), which is consistent with the observation of \( \sim 2–10 \times 10^{37} \text{ erg s}^{-1} \) (Stella et al. 1987). During the recovery of a stable mass transfer, both the mass-loss rate of donor star and the absolute value of orbital-period derivative should decrease.
5. We also simulate the evolution when the mass fed onto the CB disk is $\Delta M_{\text{CB}} = 10^{-9} M_\odot$ and $10^{-7} M_\odot$. Compared to the case when $\Delta M_{\text{CB}} = 10^{-8} M_\odot$, the evolution in the former case is similar, but there is no orbital-period decrease phase since the CB disk mass is much lower. In the latter case, a heavier CB disk induces a much faster evolution with a higher mass-transfer rate. At $P \sim 685$ s, the evolutionary age and the mass-transfer rate are $\sim 1.2 \times 10^6$ year and $\sim 2 \times 10^{-8} M_\odot$ yr$^{-1}$, respectively. Meanwhile, the simulation produces longer timescales.

Figure 3. Evolution of angular-momentum loss rate (left panel) induced by gravitational radiation and the CB disk, and evolution of the derivative rate of donor star radius and Roche lobe radius of the donor star (right panel) for Model 2.

Figure 4. Evolution of donor mass (top left panel), mass-loss rate (bottom left panel), orbital period (top right panel), and orbital-period derivative (bottom right panel) for a UCXB with the same initial parameters as Figure 2. The meaning of the different curves is also the same as in Figure 2.
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5. Summary and Discussion

Mass transfer from the less massive donor star to the more massive accretor always induces an expanding orbit. In the case of stable mass transfer, the orbital-period derivative is proportional to the mass-transfer rate and the rate of angular momentum loss (Di Salvo et al. 2008). Therefore, the negative orbital-period derivative of 4U 1820 remains mysterious for a white dwarf binary. In this work, we propose a CB disk scenario with a cycle-mass feed to interpret the anomalous orbital-period derivative of this source. In our model, the runaway burning process during a superburst event may carry away the material of a burning layer. If a small fraction of the material feeds a CB disk around the binary rather than leaving it, the related abrupt change in the total angular-momentum loss rate destroys the condition for a stable mass transfer, and induces the observed negative orbital-period derivative during the recovery of stable mass transfer.

Although the mass of the burning-carbon layer on the neutron star’s surface is only $\sim 5 \times 10^{-8} M_\odot$, during normal superburst events, we assume that some rare superbursts with a probability of 0.1% have a burning-layer mass of $\sim 5 \times 10^{-7} M_\odot$. In our calculations, rare superbursts are assumed to recur on a cycle period of 10,000 year, and 2% of the burning-layer mass feeds into a CB disk around the binary. In principle, photo-evaporation processes by the neutron star’s spin-down energy would decrease the mass of the CB disk (Antoniadis 2014). However, the mass-loss rate of the CB disk sensitively depends on the photo-evaporation efficiency, the binary separation, and the spin period of the pulsar (Alexander et al. 2006; Owen et al. 2012; Chesneau 2013). Therefore, we simply assume that the CB disk loses 0.1% of its current mass every year. Our numerical calculations show that such a CB disk model can account for the donor star mass, orbital period, and orbital-period derivative observed in 4U 1820. If the rare superburst events have a recurrence time of 10,000 year, the CB disk model predicts a 900 year timescale in the period-decreasing stage, and gives a probability of $\sim 9\%$ to observe a negative period derivative. Because of the recovery of stable mass transfer, the absolute value of orbital-period derivative should slowly decrease, which can be tested by future further observations. In addition, the continuum contribution of dust emission from the CB disk could be observed in the L band (3–4 $\mu$m) (Spruit & Taam 2001), and we expect future detailed multi-waveband observations for 4U 1820 to confirm or refute our scenario.

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