Repeating Ultraluminous X-Ray Bursts and Repeating Fast Radio Bursts: A Possible Association?

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Abstract

Ultraluminous X-ray bursts (ULXBs) are ultraluminous X-ray flares with a fast rise (~1 minute) and a slow decay (~1 hour), which are commonly observed in extragalactic globular clusters. Most ULXBs are observational one-off bursts, whereas five flares from the same source in NGC 5128 were discovered by Irwin et al. in this article, we propose a neutron star (NS)–white dwarf (WD) binary model with super-Eddington accretion rates to explain the repeating behavior of the ULXB source in NGC 5128. With an eccentric orbit, the mass transfer occurs at the periastron where the WD fills its Roche lobe. The ultraluminous X-ray flares can be produced by the accretion column around the NS magnetic poles. On the other hand, some repeating fast radio bursts (FRBs) were also found in extragalactic globular clusters. Repeating ULXBs and repeating FRBs are the most violent bursts in the X-ray and radio bands, respectively. We propose a possible association between the repeating ULXBs and the repeating FRBs. Such an association is worth further investigation by follow-up observations on nearby extragalactic globular clusters.

Unified Astronomy Thesaurus concepts: Compact binary stars (283); High energy astrophysics (739); X-ray transient sources (1852); Radio transient sources (2008)

1. Introduction

Some ultraluminous X-ray bursts (ULXBs) have been discovered in recent works (e.g., Sivakoff et al. 2005; Jonker et al. 2013; Irwin et al. 2016). These bursts rise rapidly within 1 minute of the peak luminosities, maintain a roughly steady ultraluminous state for several hundred seconds, and then decay to the preflare level within a few thousand seconds. The peak luminosities of ULXBs (\(\gtrsim 10^{38}\) erg s\(^{-1}\)) should be super-Eddington for a neutron star (NS), which are higher than the peak luminosities of type-I X-ray bursts (\(\sim 10^{37}\)–\(10^{38}\) erg s\(^{-1}\); e.g., Galloway et al. 2008). For the Eddington limit of a black hole (BH), it can be estimated from most of the ULXBs that the peak luminosities are super-Eddington for a stellar-mass BH (\(M_{\text{BH}} \sim 10 M_\odot\)) or sub-Eddington for an intermediate-mass BH (IMBH; \(M_{\text{BH}} \sim 10^{-2} M_\odot\)). Some studies have proposed explanations for ULXBs, such as the shock breakout from a core-collapse supernova (e.g., Soderberg et al. 2008), the tidal stripping of a white dwarf (WD) by an IMBH (Shen 2019), and the merger of binary NSs (e.g., Xue et al. 2019).

Most of the ULXBs are observational one-off bursts, e.g., the ULXBs observed in M86 (Jonker et al. 2013) and in NGC 4636 (Source 1 in Irwin et al. 2016), whereas two ULXB sources show repeating behaviors, i.e., two fast flares discovered in NGC 4697 (Sivakoff et al. 2005) and five flares discovered in NGC 5128 (Source 2 in Irwin et al. 2016). Sivakoff et al. (2005) showed that the ULXBs in NGC 4697 have a peak luminosity of \(\sim 6 \times 10^{39}\) erg s\(^{-1}\), a duration of \(\sim 70\) s, and a count rate ratio of the flare to the persistent emission of \(\sim 90\). For Source 2 in Irwin et al. (2016), four flares were revealed by the Chandra data, and the fifth flare was observed by XMM-Newton. The luminosities of persistent emission and peak flare are \(\sim 4 \times 10^{37}\) erg s\(^{-1}\) and \(\sim 8 \times 10^{39}\) erg s\(^{-1}\), respectively, which implies an increase of a factor of \(\sim 200\) within 1 minute. The optical counterpart is either a massive globular cluster (called GC 0320; e.g., Harris et al. 1992), or an ultracompact dwarf companion galaxy of NGC 5128 (Irwin et al. 2016).

Maccarone (2005) suggested that the ULXBs discovered in NGC 4697 could be produced by the accreting eccentric binaries in globular clusters, which accrete more rapidly at the periastron than during the rest of the binary orbit. They predicted that the repeating ULXB source is likely to be periodic if adequate sampling is provided. For the ULXBs observed in NGC 5128, Irwin et al. (2016) showed that the fast rise and the slow decay of flares seem to be similar to that of type-I bursts from Galactic NSs. However, the peak luminosities of the ULXBs are 1–2 orders of magnitude higher than that of type-I bursts, which are typically near the Eddington limit of an NS. Alternatively, the highly super-Eddington accretion onto an NS or a stellar-mass BH can satisfy the limitations of peak luminosities. The flares may be observed at the periastron when the donor star moves around the central object in an eccentric orbit (Irwin et al. 2016). Moreover, Shen (2019) showed that the ULXBs could be explained as the result of accretion onto an IMBH during the periastron passage of a WD in an eccentric orbit.

In this article, we focus on the repeating ULXB source in NGC 5128 owing to the detected multiple flares. We first propose an NS–WD binary model with an eccentric orbit to explain the repeating behavior of the ULXB source in NGC 5128. The system has a super-Eddington accretion rate. At the periastron, the mass transfer occurs when the WD fills its Roche lobe. The accreting NSs with super-Eddington accretion rates may not be rare in the ultraluminous X-ray populations consisting of NSs (more than 100 times Eddington; e.g., Bachetti et al. 2014; Fürst et al. 2016; Israel et al. 2017;
Carpano et al. 2018; Chandra et al. 2020; Quintin et al. 2021). According to our model, the information of the orbital period may be revealed by the observed flares. Thus, we manage to derive the plausible orbital period of the ULXB source in NGC 5128. Some methods have been proposed to search for periods when only a few events were observed (e.g., Rajwade et al. 2020; Katz 2022), which are helpful to derive the plausible orbital period of this ULXB source.

The remainder of this article is organized as follows. The NS–WD binary with a super-Eddington accretion rate is illustrated in Section 2. The plausible periodicity of the ULXB source in NGC 5128 is studied in Section 3. The relations between the orbital period, the eccentricity of the orbit, the WD mass, and the NS mass are shown in Section 4. A possible association between the repeating ULXBs and the repeating fast radio bursts (FRBs) is proposed in Section 5. Conclusions and discussion are presented in Section 6.

2. NS–WD Binary Model

In this section, we propose an NS–WD binary model with a super-Eddington accretion rate to explain the repeating behavior of the ULXB source in NGC 5128. The system consists of a magnetic WD and an NS with strong dipole magnetic fields. As illustrated in Figure 1, the NS–WD binary system is in an eccentric orbit. At the periastron, the mass transfer occurs from the WD to the NS through the inner Lagrange point L1 when the WD fills its Roche lobe. For other positions on the eccentric orbit, since the Roche lobe is not filled by the WD, the mass transfer is interrupted. Due to the viscous processes, the accreted materials from the WD can be fragmented into a number of parts. The accretion flow can be truncated by the magnetic field near the magnetospheric radius $R_M$, defined as the location where the magnetic pressure balances the ram pressure of the accretion flow (e.g., Kaaret et al. 2017). Around this location, the magnetized materials from the WD are governed by the magnetic field lines and leave the disk to fall onto a small area around the NS magnetic poles (e.g., Pringle & Rees 1972), yielding an accretion column or funnel. The accretion column can be maintained since the radiation pressure is balanced by the magnetic pressure in the column. The ultraluminous X-ray radiations can be produced from the accretion column. There may be two reasons for the X-ray luminosity of the highly magnetized NS with an accretion column that can exceed the Eddington limit. One is that the scattering cross section of the column can be far below the Thomson value (e.g., Basko & Sunyaev 1976). The other reason is that the radiation can escape from the sides of the column, perpendicular to the incoming flow of the magnetized materials (e.g., Lyubarskii & Syunyaev 1988). If the NS magnetic field is sufficiently high, e.g., $B_{NS} > 10^{14}$ G, then the X-ray luminosity can reach the values of the order of $10^{40}$ erg s$^{-1}$ (Mushotuk et al. 2015), which attains the peak luminosities of ULXBs detected in NGC 5128 (Irwin et al. 2016). For persistent emissions before and after the flares ($L \sim 10^{37}$ erg s$^{-1}$), the collisions of the accreted materials with the NS disk may play an important role.

On the other hand, King (2007) proposed that due to the conservation of angular momentum, the WD may be kicked away after the Roche-lobe overflow process for $q < 2/3$, where $q$ is defined as the mass ratio of the WD to the NS. After that, the gravitational radiation is an essential mechanism to enable the WD to refill its Roche lobe. Hence, the NS–WD binary system becomes semidetached again, and the next mass transfer can recur. That is, for the binary with $q < 2/3$, the Roche-lobe overflow should be an intermittent process. For a typical NS mass, $1.4 M_\odot$, the sporadic type of Roche-lobe overflow may be common for a semidetached binary system with a WD donor ($M_{WD} \lesssim 0.6 M_\odot$). Therefore, the ULXB is not always observable in each orbital cycle.

3. Possible Orbital Periods

According to the NS–WD binary model described in Section 2, the orbital period may be revealed by the analyses of the observed repeating ULXBs. In this section, we manage to derive several possible orbital periods of the ULXB source in NGC 5128.

We refer to the method of Rajwade et al. (2020), searching for the period with the narrowest folded profile. Rajwade et al. (2020) folded the arrival time of FRB 121102 at all distinguishable trial periods between 2 and 365 days. Then, they measured the length of the longest contiguous phase without any sourcing activity. Higher values express that the activity of the FRBs is concentrated within a narrower phase window, which indicates a periodic activity pattern. According to this method, the trial period for FRB 121102 has been found to be $P \approx 159$ days, with an inactive contiguous phase of 53% (Rajwade et al. 2020).

For the repeating ULXB source in NGC 5128, five flares were recorded in Irwin et al. (2016): four were observed with Chandra on 2007 March 30, 2007 April 17, 2007 May 30, and...
2009 January 4, respectively; the fifth flare was observed with XMM-Newton on 2014 February 9. Another possible flare from the same location of NGC 5128 was observed by Swift on 2013 July 31 (the information is originally from the talk of J. A. Irwin in the AAS HEAD Meeting in 2017 August and also from J. A. Irwin, private communications). Swift observed seven photons in 300 s (a total observation time of \( \sim 3400 \) s). The count rate of the flare (\( \sim 0.023 \) counts s\(^{-1}\); time bin of 300 s) is far higher than the count rates before and after the flare (\( \sim 0.001 \) counts s\(^{-1}\)). Thus, it may be regarded as another flare from the same ULXB source in NGC 5128.

Based on the start time of six flares, the minimum interval between two adjacent detected flares is \( \sim 18 \) days, which should be an upper limit of the orbital period of the ULXB source in NGC 5128. Hence, based on the method of Rajwade et al. (2020), we folded the start time of six flares at all distinguishable trial periods between 0.2 days and \( \sim 18 \) days. The fraction of ULXB inactivity as a function of the period is shown in the upper panel of Figure 2. Three significant trial periods can be found, i.e., \( P = 0.6428 \), 2.6485, and 6.0275 days, which display the inactive contiguous phases of 80%, 83%, and 88%, respectively. By folding the start time of six flares with three trial periods, the activity profiles of the ULXBs are shown in the lower panel of Figure 2. The histograms of different colors exhibit the distinct plausible activity windows of the repeating ULXB source in NGC 5128.

Summing up all of the available data (up to 2015 May 17), Irwin et al. (2016) evaluated the recurrence rate (defined as the total observation time divided by the number of flares) of one flare every \( \sim 1.8 \) days (a total observation time of \( 7.9 \times 10^5 \) s divided by five flares) and the duty cycle of \( \sim 2.5\% \) for the repeating ULXB source in NGC 5128. For now, six flares were observed in a total observation time of \( \sim 1.2 \times 10^6 \) s, yielding the recurrence rate of one flare every \( \sim 2.3 \) days. Based on our model, since the Roche-lobe overflow should be an intermittent process, the ULXB is not always observable in each orbital cycle. Thus, the orbital period of the ULXB source in NGC 5128 is likely \( P_{\text{orb}} \lesssim 2.3 \) days. Thus, among the three possible orbital periods, 0.6428 and 2.6485 days are more preferred. We would point out that only one period can be correct and two wrong periods show up, which indicates that only six observed flares are not sufficient enough to well constrain the orbital period.

![Figure 2.](image-url)
4. Masses of the Compact Objects

Three possible orbital periods of the repeating ULXB source in NGC 5128 have been found in Section 3. We consider that the orbital periods are related to the orbital period of the NS–WD binary. In addition to the explanation of the super-Eddington accretion of an NS, the ULXBs can also be considered to be produced by the sub-Eddington accretion of an IMBH. Shen (2019) proposed that ULXBs can be explained by the accretion onto an IMBH during the periastron passage of a WD in an eccentric orbit. Moreover, they predicted that the interval between two recurrent flares may be the eccentric orbital period of the WD. A large eccentricity $e$ of the orbit ought to be considered to satisfy the restriction of the long orbital period (e.g., $P \sim 1$ day, $e \sim 0.97$; see Equation (8) in Shen 2019). For the binary systems with different types (or masses) of central objects, i.e., an NS or an IMBH, in the following section, we try to confirm whether the periodicity of the ULXB source in NGC 5128 can be affected.

The dynamic equation of the binary system can be expressed as

$$\frac{G(M_1 + M_{WD})}{a^3} = \frac{4\pi^2}{P_{orb}^2},$$

where $G$ is the gravitational constant, $M_1$ and $M_{WD}$ are the masses of the central object (i.e., an NS or an IMBH) and the WD, respectively, $a$ is the binary separation, and $P_{orb}$ is the orbital period. The Roche-lobe radius $R_L$ for the WD at the periastron can take the form (Eggleton 1983)

$$\frac{R_L}{a(1 - e)^{1/3}} = \frac{0.49q^{2/3}}{0.69q^{2/3} + \ln(1 + q^{1/3})},$$

where $q$ is the mass ratio defined as $q = M_{WD}/M_1$. The WD radius $R_{WD}$ can be expressed as (Tout et al. 1997)

$$R_{WD} = 0.0115\frac{R_\odot\sqrt{(M_{Ch}/M_{WD})^{2/3} - (M_{WD}/M_{Ch})^{2/3}}}{\sin^2\iota},$$

where $M_{Ch}$ is the Chandrasekhar mass limit $M_{Ch} = 1.44 M_\odot$. According to the assumption that the WD fills its Roche lobe at the periastron, i.e., $R_{WD} = R_L$, once $M_1$, $M_{WD}$, and $e$ are given, the orbital period can be derived by Equations (1)-(3). The relationships between the orbital period $P_{orb}$ and the mass of the central object $M_1$ for the distinct given eccentricities $e$ and the WD masses $M_{WD}$ are shown in Figure 3. The lines of different colors represent different masses of the WDs, i.e., $0.02 M_\odot$ (black), $0.05 M_\odot$ (blue), and $0.1 M_\odot$ (red). Moreover, the solid and dashed lines express $e = 0.95$ and 0.99, respectively. It is seen from Figure 3 that once the mass of the WD $M_{WD}$ and the eccentricity of the orbit are determined, the orbital period $P_{orb}$ of the system nearly remains constant for varying $M_1$. In other words, for such an accretion model, a large eccentricity is required to interpret the repeating ULXB source in NGC 5128 no matter if the accretor is an NS, a stellar-mass BH, or an IMBH. For the possible orbital periods of this source (the green stars shown in Figure 3), $e > 0.95$ is required for $M_{WD} = 0.1 M_\odot$ and $M_1 = 1.4 M_\odot$.

In addition, a simple analytic relation between $P_{orb}$, $M_{WD}$, and $e$ can refer to Equation (7) of Gu et al. (2020). Such a simple relation is independent of $M_1$. Hence, it is reasonable that the mass of the central object $M_1$ cannot validly influence the orbital periods of the eccentric binary systems. That is, the orbital period of the repeating ULXB source in NGC 5128 is mainly related to the mass of the WD and the eccentricity of the orbit.

5. Possible Association between ULXBs and FRBs

In our previous studies, the NS–WD binary model with super-Eddington accretion rates has been proposed to explain the repeating FRBs. In that model, the repeating FRBs can be explained as the result of the magnetic reconnection when the accreted magnetized materials approach the NS surface (Gu et al. 2016, 2020; Lin et al. 2022), or the radio radiations of the narrowly collimated jet (Chen et al. 2021). FRBs are millisecond-duration radio bursts with the isotropic equivalent luminosities of $\sim 10^{38-42}$ erg s$^{-1}$ (for reviews, see Cordes & Chatterjee 2019; Petroff et al. 2019). Recently, FRB 20200120E was discovered to be located in a globular cluster associated with M81 (Kirsten et al. 2022). This source is the first detected repeating FRB located in an extragalactic globular cluster, whereas other located repeating FRBs are related to the nearby star-forming regions of the host galaxies (e.g., Bassa et al. 2017; Tendulkar et al. 2021). No X-ray source at the location of FRB 20200120E has been found in archival Chandra observations, which results in a 0.5–10 keV luminosity upper limit of $2 \times 10^{37}$ erg s$^{-1}$ at the distance of 3.6 Mpc (Kirsten et al. 2022). Kirsten et al. (2022) proposed that the ultraluminous X-ray sources associated with FRB 20200120E can be ruled out by the X-ray limit unless the X-ray luminosities of these sources vary in time by more than 2 orders of magnitude. Based on the burst arrival times of FRB 20200120E, Nimmo et al. (2022b) found a possible 12.5 day activity period, which may require more detected bursts to test the significance of this period. On the other hand, in our opinion, the repeating ULXB source has the possibility to be
associated with the repeating FRB source owing to its extremely violent burst ability. The repeating ULXB source and the repeating FRB source show the most violent bursts in the X-ray and the radio bands, respectively. In addition, our NS–WD binary model with super-Eddington accretion rates can work well for both of these two systems. Moreover, Katz (2021) proposed that an NS and a close binary companion (likely a WD) can be responsible for the observed long-lived repeating FRB sources in globular clusters. Thus, we propose that a possible association may exist between the repeating ULXB source and the repeating FRB source. Such an association is worth further investigation by follow-up observations on nearby extragalactic globular clusters.

The burst timescales of \(~60\) ns to 5 \(\mu\)s observed in FRB 20200120E indicate a light-travel size of \(~20–1500\) m (Majid et al. 2021), which supports a magnetospheric origin of the FRB radiations (e.g., Zhang 2020). Nimmo et al. (2022a) proposed that the magnetic reconnection events in the close vicinity of a highly magnetized NS can produce the observed timescales and luminosities from FRB 20200120E. Thus, it is reasonable that the system consists of a magnetic WD and an NS with strong dipole magnetic fields. The schematic diagram of the general physical process is shown in Figure 1. Around the magnetospheric radius \(R_{\text{m}}\), the magnetized accreted materials are guided by the magnetic field lines and leave the disk to follow the magnetic field lines down to the polar caps of the NS. During the falling process, the magnetic reconnection may be triggered. The strong electromagnetic radiations can be released by the curvature radiation of the electrons, which move along the NS magnetic field lines with ultrarelativistic speed (e.g., Zhang & Yan 2011; Gu et al. 2016).

According to our model, the duration of an FRB may be regarded as the timescale of a magnetic reconnection. The duration \(t_d\) can be evaluated by the ratio of the NS radius \(R_{\text{NS}}\) to the Alfvén speed \(v_A\) (=\(B_{\text{NS}}/\sqrt{4\pi \rho}\); Gu et al. 2016)

\[
t_d = \frac{B_{\text{NS}}}{v_A} = 1.1 \left( \frac{R_{\text{NS}}}{10^6 \text{ cm}} \right) \left( \frac{B_{\text{NS}}}{10^{11} \text{ G}} \right)^{-1} \left( \frac{\rho}{10^3 \text{ g cm}^{-3}} \right)^{1/2} \text{ms},
\]

where \(B_{\text{NS}}\) is the magnetic flux density of the NS, and \(\rho\) is the averaged mass density of accreted materials. For the typical values \(R_{\text{NS}} = 10^6\) cm and \(\rho = 10^3\) g cm\(^{-3}\), a large magnetic flux density \((B_{\text{NS}} \gtrsim 10^{14}\) G\) is required to account for the microsecond-duration bursts of FRB 20200120E.\(^3\)

### 6. Conclusions and Discussion

In this article, we have proposed an NS–WD binary model with an eccentric orbit to explain the repeating behavior of the ULXB source in NGC 5128. The system has a super-Eddington accretion rate. Moreover, for the most violent short-duration repeating bursts in the X-ray and radio bands, i.e., the repeating ULXBs and the repeating FRBs such as FRB 20200120E, which were detected in extragalactic globular clusters, we propose that the physical processes of these two types of bursts may have a possible association. Our NS–WD binary model with super-Eddington accretion rates can account for this association. According to our model, the orbital period may be revealed by the observed repeating bursts of the ULXB source in NGC 5128. We have derived three possible periods by analyses of the detected bursts, i.e., 0.6428, 2.6485, and 6.0275 days, where the former two periods are more preferred. Whether the central object is an NS or an IMBH, a large eccentricity of the orbit is required to interpret the orbital periods, e.g., \(e > 0.95\) for \(M_{\text{WD}} = 0.1M_\odot\).

Li et al. (2021) showed that 1652 independent bursts of FRB 121102 have been detected by FAST in 59.5 hr spanning 47 days. The burst rate of FRB 121102 peaked at 122 h\(^{-1}\), then dropped dramatically afterward. The variations of the burst rates indicate the changes in the activities of FRB 121102. As the first discovered repeater, the activity timescale of FRB 121102 may be evaluated as \(\gtrsim 10\) yr. According to our model, the activity timescale of the ULXB source in NGC 5128 should be similar to that of the repeating FRBs, i.e., \(\gtrsim 10\) yr. For the ULXB source in NGC 5128, six flares were observed from 2007 to 2014. After that, no significant flares were discovered from the same location, implying that the \(\gtrsim 10\) yr activity timescale for the ULXB source in NGC 5128 is reasonable.

According to our model, a large eccentricity \(e\) of the orbit is required to interpret the plausible orbital period of the ULXB source in NGC 5128. There are two possibilities for forming an NS–WD binary with a large eccentricity. The first is caused by the natal kick of the supernova explosion in a binary channel, which may correspond to a young NS. The other possibility is that a WD can be tidally captured by an old NS (e.g., Clark 1975). The globular clusters host old stellar populations and have extreme stellar densities. Thus, in the globular clusters, the second possibility should play an essential role in the formation of an NS–WD binary with a large eccentricity.

The distance of NGC 5128 is 3.8 Mpc (Harris et al. 2010), and the distance of M81 is 3.6 Mpc (Freedman et al. 1994). The compact binaries are efficiently formed inside the globular clusters of these nearby extragalactic galaxies. Follow-up observations on nearby extragalactic globular clusters may help to examine the potential association between the repeating ULXBs and the repeating FRBs.

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\(^3\) For the mass density in the atmosphere of a WD, continuous variation exists from large interior values to essentially zero. For simplicity, following Gu et al. (2016), we use an averaged mass density \(\rho = 10^3\) g cm\(^{-3}\) for the accreted materials.
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