A TIDAL CAPTURE FORMATION SCENARIO FOR THE ACCRETING PULSAR IGR J17480–2446 IN TERZAN 5

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ABSTRACT

The low mass X-ray binary (LMXB) IGR J17480–2446 is an 11 Hz accreting pulsar located in the core of the globular cluster Terzan 5. This is a mildly recycled accreting pulsar with a peculiar evolutionary history since its total age has been suggested to be less than a few hundred Myr, despite the very old age of Terzan 5 (∼12 Gyr). Solving the origin of this age discrepancy might be very valuable because it can reveal why systems like IGR J17480–2446 are so rare in our Galaxy. We have performed numerical simulations (dynamical and binary evolution) to constrain the evolutionary history of IGR J17480–2446. We find that the binary has a high probability to be the result of close encounters, with a formation mechanism compatible with the tidal capture of the donor star. The result reinforces the hypothesis that IGR J17480–2446 is a binary that started mass transfer in an exceptionally recent time. We also show that primordial interacting binaries in the core of Terzan 5 are strongly affected by a few hundred close encounters (fly-by) during their lifetime. This effect might delay, accelerate or even interrupt the Roche lobe overflow (RLOF) phase. Our calculations show that systems of this kind can form exclusively in dense environments like globular clusters.

Keywords: stars: neutron — X-rays: stars — stars: dynamics

1. INTRODUCTION

The 11 Hz accreting pulsar IGR J17480–2446 is to date the only mildly recycled accreting pulsar known in our galaxy (see Zolotukhin et al. 2017 for an extra-galactic analogue). This is an accreting neutron star in the process of being spun-up via channeled accretion and its spin frequency is smaller than the ∼50–100 Hz required to form an accreting millisecond X-ray pulsar (AMXP). To date 19 AMXPs have been identified, with orbital periods ranging from 19 hr down to 40 minutes and with neutron star spin frequencies between 162 and 599 Hz (see Patruno & Watts 2012 for a review and Strohmayer & Keek 2017 for the latest discovery). In addition, we know in our galaxy three LMXBs and one intermediate mass X-ray binary (Her X-1) containing slow X-ray pulsars with spin frequency of 0.1–1 Hz and at least four symbiotic X-ray binaries with neutron star accretors. The three slow LMXBs and Her X-1 are different from the 19 AMXPs because of their strong magnetic dipole moments of the order of \( \mu \approx 10^{30} \text{ G cm}^3 \) (e.g., D’Ai et al. 2015), whereas AMXPs have \( \mu \approx 10^{26} \text{ G cm}^3 \). The mildly recycled pulsar IGR J17480–2446 has a dipolar magnetic moment which is constrained to be in the range \( \mu \approx 10^{27} – 10^{28} \text{ G cm}^3 \) and it has an orbital period of 21.3 hr with a measured mass function giving a minimum donor mass of \( 0.4 M_\odot \) (Papitto et al. 2011, 2012; Cavecchi et al. 2011; Patruno et al. 2012). It has been demonstrated that, at least during the outbursts, IGR J17480–2446 is in a clear spin-up phase whose magnitude (\( \sim 10^{-12} \text{ Hz s}^{-1} \)) would turn the system into an AMXP in the next few tens of million years (Patruno et al. 2012; Papitto et al. 2012). However, this seems to be at odds with the very long phases that binaries with parameters similar to IGR J17480–2446 spend in Roche lobe contact (Podsiadlowski et al. 2002), which can last for about 1 Gyr or more. Patruno et al. (2012) proposed therefore that IGR J17480–2446 is in an exceptionally early RLOF phase although the reason on why we are witnessing this unlikely event remains an open problem.

An interesting property of IGR J17480–2446 is that it resides in the very massive and centrally concentrated globular cluster Terzan 5. The cluster age is constrained to be 12 ± 1 Gyr with a possible second population of stars, comprising about 40% of the cluster mass and formed in a more recent epoch, with an age of 4.5 ± 0.5 Gyr (Ferraro et al. 2016, 2009). The two populations of stars have different compositions of \( Z = 0.01, Y = 0.29 \) (the old one) and \( Z = 0.03, Y = 0.26 \) (the younger one) which is very atypical for globular clusters. Terzan 5 is also peculiar because it hosts an impressive number of compact objects, with 37 radio pulsars discovered so far (Lyne et al. 1990, 2000; Ransom et al. 2005; Hessels et al. 2006; see also the on-line catalog4) and at least 31 X-ray sources.

This large number of compact objects might be connected with the role of dynamical encounters in the cluster. In particular, the fact that IGR J17480–2446 lies within the core radius of Terzan 5 (Heinke et al. 2006), strongly suggests that dynamical encounters might also have played a significant role in the formation and evolution of this binary, which could perhaps explain the peculiar evolutionary stage in which it is currently observed (but see also Patruno et al. 2012 and Tauris et al. 2013 for a formation scenario that involves accretion induced collapse of a white dwarf).

Patruno et al. (2012) provided an analytic study of the three evolutionary epochs (magnetic-dipole dominated, wind fed and RLOF) that a typical neutron star LMXB follows during its lifetime and concluded that IGR J17480–2446 is in an exceptionally early RLOF phase with a slightly evolved donor star (a sub-giant) close to the turn off mass of Terzan 5 (\( M \sim 0.9 – 1.1 M_\odot \), depending to which of the two stellar populations does it belong). The total age of the binary was constrained to be less than a few hundred Myr when considering the duration of each of the three evolutionary epochs. The
evolution of IGR J17480–2446 seems to be anomalous in this sense, and its location in the globular cluster Terzan 5 might help to explain why it is so. Jiang & Li (2013) in particular, provided a first discussion of this possibility and suggested that IGR J17480–2446 has been formed by an exchange interaction in between a binary and an isolated recycled pulsar (or a binary containing the current pulsar and the current donor star).

In this paper we present new results that help to further constrain the history of IGR J17480–2446. We present dynamical and binary evolution calculations to help determine whether IGR J17480–2446 is a primordial binary or whether its accretion history has been strongly affected by the multiple interactions that occur in the globular cluster core. In Section 2 we describe the numerical codes used in our calculations. In Section 3 we present our results and we investigate three possible scenarios for the origin of the system: exchange interaction (Section 3.1), tidal capture (Section 3.2) and accretion induced collapse (Section 3.3). In Section 4 we expand our results by broadly considering the effect that close encounters have on the evolution of interacting binaries located in the dense core of clusters like Terzan 5. In Section 5 we outline our conclusions.

2. NUMERICAL SIMULATIONS

We have carried a set of dynamical and binary evolution calculations to test possible formation scenarios and evolutionary histories of IGR J17480–2446. We first begin by describing the dynamical simulations and then we outline the main features of the binary evolution code used in this work.

2.1. Dynamical Simulations

Dense concentrated environments like the core of Terzan 5 play a critical role in determining the evolution of binaries. We check here with which probability close encounters a

2.1.2. Three-body Encounters

At each step, the probability of a close encounter between the simulated binary and a single star is evaluated. If the probability is found to be sufficiently high (on the basis of a random number), the parameters of the encounter (relative velocity, impact parameter and orientation angles) are also generated. The criteria to evaluate the probability of an encounter, as well as the physical parameters of the encounter, are described in detail in (Sigurdsson & Phinney 1995). Three-body encounters are implemented by means of a 4th-order Runge-Kutta integration scheme with adaptive step size and quality control, and with the requirement that the angular momentum is conserved to one part in $10^5$. This guarantees that the energy is conserved to better than one part in $10^7$ during the three-body encounter (Sigurdsson & Phinney 1993).

2.1.3. Binary Initial Conditions

An ensemble of binaries was evolved for a fixed time $t = 12$ Gyr, in the described model of globular cluster. The primary is fixed to be a neutron star and its initial mass ($m_1$) is set to 1.4 $M_\odot$. The mass of the secondary ($m_2$) is drawn at random from a Salpeter (1955) initial mass function, requiring that $0.1 \leq m_2/M_\odot \leq 1.2$. The initial semi-major axis $a_{in}$ is randomly drawn from a uniform log ($a$) distribution (requiring $7 \times 10^{-3} \leq a_{in}/AU \leq 1 \times 10^2$). Finally, the initial eccentricity $e_{in}$ is randomly drawn from a distribution $P(e) = 2e$ ($0 \leq e_{in} < 1$).

2.2. Binary Evolution Calculations

For our binary evolution calculations we use the Modules for Experiments in Stellar Astrophysics (MESA; Paxton et al. 2011, 2013, 2015), updated to its latest release (9575, 17 Feb. 2017). The binary evolution code is used to investigate a number of effects not present in the dynamical simulations, in particular the effect of the tidal interaction on the synchronization and circularization time. We first created Zero Age Main Sequence (ZAMS) models starting from a pre-main sequence model with a specific metallicity and helium abundance ($Z = 0.01, Y = 0.29$ and $Z = 0.03, Y = 0.26$, selected to match the two populations of Terzan 5, see Figure 1).

Then we evolved a set of 10 stars with mass 0.8, 0.9, 1.0, 1.1 and 1.2 $M_\odot$ for about 11 and 5 Gyr for the low and high metallicity population, respectively. Then we used the evolved stellar models in a grid of binaries with initial orbital period between 10 and 30 hours and with an accretor mass between 1.2
and 2.3 $M_\odot$. The binary eccentricity was also included as a parameter, spanning values between 0 and 0.95. Since we have found that the dynamical encounters will perturb the orbit (along with the eccentricity) of IGR J17480–2446 on average every 30 Myr, we want to explore which of our binaries lose their eccentricity to within the currently observed upper limits of $e < 0.001$ (Papitto et al. 2012; Patruno et al. 2012). The initial stellar angular rotation is treated as uniform and is taken to vary between $\Omega_\ast = 10^{-6}$ rad s$^{-1}$ and $\Omega_\ast = 6.1 \times 10^{-5}$ rad s$^{-1}$. A summary of the grid of values used is reported in Table 1.

The circularization of the orbit and the synchronization of the companion rotation occurs via tidal interaction and is treated according to Hut (1981) for stars with a convective envelope. The tidal evolution of the orbit proceeds on a timescale:

$$T = \frac{R^3}{GM\tau} = \frac{1}{4\pi^2} \left( \frac{P_s}{\tau} \right) P_s$$

where $M$ and $R$ are the donor mass and radius, $G$ is the gravitational constant, $\tau$ is a lag used in the weak friction model (see Darwin 1879; Hut 1981) and $P_s$ is the orbital period of a particle grazing the surface of the donor star.

### 3. RESULTS

As a consequence of dynamical encounters, the binaries in Terzan 5 can undergo exchange interactions, during which one of the two stars of the binary is exchanged with an incoming star. Dynamical processes can also create new binaries when a star passes sufficiently close to another star so that tidal interactions can bind the two objects together. Furthermore, even if the exchange or the tidal interactions do not take place in large number, we need to consider the occurrence of a large number of stellar fly-bys. Finally, if the accretor is a massive white dwarf with stable hydrogen burning, then its mass can increase above the Chandrasekhar limit and collapse to form a neutron star. In the following, we thus consider these three scenarios for the formation of IGR J17480–2446.

#### 3.1. Scenario I: Exchange Interaction

Table 2 shows that exchanges are very frequent for the considered binaries: about 62% of the simulated binaries undergo at least one exchange during the simulation. The outcome of an exchange is the ejection of the secondary star in 95% of cases (and the neutron star retained in the system) which can be easily understood as the neutron star is by far the most massive object in the initial binary.

The average mass of the secondary at the end of the simulation is $\langle M_{2,\text{fin}} \rangle \approx 1.1 M_\odot$. We remind that the initial average mass of the secondary (given the assumed Salpeter initial mass function and mass range) is $\langle M_{2,\text{init}} \rangle = 0.23 M_\odot$. This implies a significant increase of the secondary mass as a consequence of exchanges.

Finally, the average number of exchanges per binary during the entire simulation is $\langle N_{\text{exch}} \rangle = 1.22$. This implies that the exchange rate from the simulation is $\nu_{\text{exch}} = 1.02 \times 10^{-10}$ yr$^{-1}$, i.e. that the exchange timescale is $\tau_{\text{exch}} \approx 10$ Gyr.

#### 3.1.1. Binary Orbital Properties

The simulations give us insight about the orbital properties of the binaries, and in particular about the final semi-major axis $a_{\text{fin}}$ and eccentricity $e_{\text{fin}}$. The values of $a_{\text{fin}}$ and $e_{\text{fin}}$ that we show must be considered as values before the start of mass transfer, as the BEV code does not include mass transfer and circularization. Figure 2 shows the distribution of $a_{\text{fin}}$ (we remind that the distribution of $a_{\text{fin}}$ was uniform in logarithm and in the $7 \times 10^{-3} - 1 \times 10^2$ AU range). The final distribution is still approximately uniform in logarithm (except for the low/high $a_{\text{fin}}$ tails) and spans the $2 \times 10^{-3} - 2 \times 10^3$ AU range. The vertical dotted line in Figure 2 shows the current orbital separation of IGR J17480–2446 ($\approx 0.024$ AU for an assumed total system mass of 2.3 $M_\odot$), which is in the allowed range. Figure 3 shows the relative change of the semi-major axis $a$, defined as $\Delta a / a \equiv (a_{\text{fin}} - a_{\text{init}}) / a_{\text{init}}$, $\sim 66$ per cent of binaries

### Table 1: Binary Evolution Grid.

| Parameter                        | Initial Value | Final Value | Step Size |
|----------------------------------|---------------|-------------|-----------|
| Orbital Period (hours)           | 15            | 31          | 2         |
| Eccentricity                     | 0             | 0.95        | 0.2       |
| Donor Mass ($M_\odot$)           | 0.8           | 1.2         | 0.15      |
| Neutron Star Mass ($M_\odot$)    | 1.2           | 2.1         |           |
| Donor Angular Velocity (rad s$^{-1}$) | $10^{-6}$   | $6.1 \times 10^{-5}$ | $10^{-5}$ |

$P_{\text{exch}}$ is the probability that a simulated binary makes at least one exchange during the simulation ($t = 12$ Gyr). $P_{\text{exch},2}$ is the probability that a simulated binary makes at least one exchange in which the secondary star is ejected, whereas the neutron star remains in the system, during the simulation. $\langle m_{2,\text{fin}} \rangle$ is the average mass of the companion at the end of the simulation. $\langle N_{\text{exch}} \rangle$ is the average number of exchanges per binary (including even binaries that do not undergo any exchanges), during the simulation. $\tau_{\text{exch}}$ is the exchange timescale.

![Figure 1](image)

**Figure 1.** Trajectories of central conditions (x-axis: central density, y-axis: central temperature) for pre-main sequence stars evolved with MESA up to the ZAMS. The different trajectories refer to masses from 0.63 $M_\odot$ (bottom curve) to 1.55 $M_\odot$ (top curve) in logarithmic steps of 0.03. The red and dark blue lines refer to the different compositions used in this work and the end of each line at the top right marks the start of the ZAMS. All stellar models used in this paper have initial (ZAMS) conditions generated by interpolating the values of the ZAMS models shown.

| Parameter                        | Initial Value | Final Value | Step Size |
|----------------------------------|---------------|-------------|-----------|
| Orbital Period (hours)           | 15            | 31          | 2         |
| Eccentricity                     | 0             | 0.95        | 0.2       |
| Donor Mass ($M_\odot$)           | 0.8           | 1.2         | 0.15      |
| Neutron Star Mass ($M_\odot$)    | 1.2           | 2.1         |           |
| Donor Angular Velocity (rad s$^{-1}$) | $10^{-6}$   | $6.1 \times 10^{-5}$ | $10^{-5}$ |

**Table 2:** Statistics of exchanges.

| Parameter                        | Initial Value | Final Value | Step Size |
|----------------------------------|---------------|-------------|-----------|
| Orbital Period (hours)           | 15            | 31          | 2         |
| Eccentricity                     | 0             | 0.95        | 0.2       |
| Donor Mass ($M_\odot$)           | 0.8           | 1.2         | 0.15      |
| Neutron Star Mass ($M_\odot$)    | 1.2           | 2.1         |           |
| Donor Angular Velocity (rad s$^{-1}$) | $10^{-6}$   | $6.1 \times 10^{-5}$ | $10^{-5}$ |

$P_{\text{exch}}$ is the probability that a simulated binary makes at least one exchange during the simulation ($t = 12$ Gyr). $P_{\text{exch},2}$ is the probability that a simulated binary makes at least one exchange in which the secondary star is ejected, whereas the neutron star remains in the system, during the simulation. $\langle m_{2,\text{fin}} \rangle$ is the average mass of the companion at the end of the simulation. $\langle N_{\text{exch}} \rangle$ is the average number of exchanges per binary (including even binaries that do not undergo any exchanges), during the simulation. $\tau_{\text{exch}}$ is the exchange timescale.
widen, as a consequence of the interactions. \(a_{\text{fin}}\) versus \(a_{\text{in}}\) are shown in Figure 4, for binaries that underwent exchange (open circles) and for binaries that did not undergo exchange (crosses). There is no significant difference between systems that underwent at least one exchange and systems that never underwent exchanges. On the other hand, there are two interesting trends. First, binaries that undergo exchanges can shrink more than binaries that do not exchange their members. This is a consequence of the larger binding-energy gain connected with exchanges. Second, it is unlikely that very hard binaries (with \(a_{\text{in}} \lesssim 0.01\) AU) undergo exchanges. The final distribution of eccentricity (\(e_{\text{fin}}\); Figure 5) shows a depletion of binaries at low (< 0.1) eccentricity (initial eccentricities were generated according to a thermal distribution between 0 and 1). This is a consequence of the high frequency of exchanges (which generally lead to an increase of eccentricity, see, e.g., Sigurdsson & Phinney 1993), combined with the absence of circularization recipes in the code. This fact is confirmed by looking at the relative change of eccentricity, defined as \(\frac{\Delta e}{e} \equiv \frac{e_{\text{fin}} - e_{\text{in}}}{e_{\text{in}}}\): about 72 per cent of the simulated systems have significantly higher eccentricity by the end of the simulation.

Another important result is that the relative variation of the semi-major axis per encounter is \(\frac{\Delta a}{a} \approx 0.15\) so that on average, the semi-major axis changes by about 15% for each encounter of the binary. Since each binary has an average of one encounter every 32 Myr, the total number of encounters each binary has done during the entire lifetime of the cluster is \(N_{\text{enc}} \approx 400\). The binary semi-major axis has been perturbed enormously during the lifetime of the system, with the companion star being pushed closer or further away from the compact object at a high rate. Despite this huge variation of the
orbital separation per encounter, the final orbital separation after \( \sim 375 \) encounters is still rather close to the initial orbital separation because the ratio between hardening and softening encounters is close to unity.

The binaries which have \( a_{\text{fin}} < a_{\text{in}} \) change their semi-major axis, on average, by a fraction: \( \langle \Delta a/a \rangle \approx -0.5 \) whereas those with \( a_{\text{fin}} > a_{\text{in}} \) drift by a total amount of \( \langle \Delta a/a \rangle \approx 3 \). This means that in the cluster lifetime “hard” binaries have a final orbital separation which is about 50% of their initial value, whereas “soft” binaries have a final orbital separation 4 times larger than the initial value.

3.1.2. Binary Evolution

If IGR J17480–2446 has been formed via an exchange interaction, then the binary needs to still dissipate its eccentricity (on average) within the next close encounter. To verify whether this is possible, we have looked at our binary evolution calculations. We find that none of our binaries is able to circularize within the 30 Myr encounter timescale, unless the initial binary eccentricity is already smaller than \( \leq 0.2 \). This means that the exchange interaction model requires substantial fine-tuning of the initial parameters.

3.2. Scenario II: Tidal Capture

Tidal interactions are not included in our dynamical calculations but they can nonetheless provide a valid scenario to explain the properties of IGR J17480–2446. A neutron star can capture an incoming star by deforming the stellar structure via tides that remove part of the kinetic energy of the incoming star. This mechanism might in principle form moderately tight binaries with orbital separations of \( 3–4 \) tidal radii (McMillan et al. 1987; Mardling 1996). This can be defined as:

\[
r_t = \left( \frac{m_1}{m_2} \right)^{1/3} R_2
\]

where \( R_2 \) and \( m_2 \) are the radius and mass of the incoming star and \( m_1 \) is the neutron star mass. If we assume a canonical 1.4 \( M_\odot \) neutron star mass and we use the actual observed and inferred donor parameters: \( m_2 \approx 1 \), \( R_2 \approx 1.3 R_\odot \) (see for example Patruno et al. 2012), then a binary with an orbital separation of \( 0.014–0.03 \) AU can be formed via tidal capture, which is within the range of the currently observed value.

Support to the tidal capture scenario comes from the fact that the orbital period of IGR J17480–2446 is surprisingly close to the bifurcation period (see Figure 6). Indeed all neutron star binaries created via tidal capture are formed with a period close to the bifurcation period, provided that their mass and radius are close to solar values (Podsiadlowski et al. 2002; Di Stefano & Rappaport 1992). The tidal capture scenario provides therefore a natural explanation to the orbital parameters of IGR J17480–2446, but it remains to be verified whether the capture rate is sufficiently high to guarantee a high probability for such an event.

Further support for the tidal capture scenario comes from the low eccentricity of the system. Indeed if IGR J17480–2446 is formed via tidal capture then it will be a very hard binary, meaning that its orbital energy is much larger than the average kinetic energy of the incoming stars interacting in close encounters. This guarantees a very quick circularization of the orbit. The current orbital binding energy of IGR J17480–2446 is:

\[
E_b = G m_1 m_2 \frac{1}{2a}
\]

which, for \( m_1 = 1.4 M_\odot \) and \( m_2 = 1 M_\odot \) gives a value of the order of \( 5 \times 10^{47} \) erg. The average kinetic energy of a star in the cluster is:

\[
E_k = \frac{1}{2} (m) v_c^2 \sim 10^{45} \text{erg}
\]

where \( \langle m \rangle \) is the average stellar mass in the cluster. Since \( E_k \ll E_b \), IGR J17480–2446 is indeed a hard binary.

The tidal capture rate can be estimated as:

\[
\Gamma_{TC} \approx \frac{4\pi r_c^3}{3} n_{NS} \Sigma \sigma_c
\]

where \( r_c \) is the core radius of the cluster (0.16 pc in our case), \( n_{NS} \) is the number densities of neutron stars in the cluster core, \( n_c \) is the cluster core density (see Section 2.1) and \( \Sigma \) is the cross section of the interaction. This latter quantity is defined as:

\[
\Sigma = \pi r_c^2 \left( 1 + \frac{2G m_1}{\sigma_c r_c} \right).
\]

The largest uncertainties in the calculation of this expression come from the poor knowledge of the total number of neutron stars in the core of Terzan 5. However, since we know that the cluster contains several tens of pulsars and X-ray binaries and it has even been suggested it might contain few hundred pulsars (H.E.S.S. Collaboration et al. 2011), we can use a lower limit of the order of \( n_{NS} \sim 10^{-2} \) pc\(^{-3} \) to estimate \( \Gamma_{TC} \). This gives a tidal capture timescale of \( \tau_{TC} \sim 0.2–8 \) Gyr, depending on the stellar mass and radius (see Figure 7). If we consider also stars that have evolved significantly off the main sequence, then the tidal capture timescale can be as short as a few tens of million years (for a \( R = 10 R_\odot \) giant star). In this case the companion of IGR J17480–2446 might be a stripped giant star, something proposed already for other sources in globular clusters (e.g., van Zyl et al. 2004). However, even when we consider main sequence and sub-giant stars with a mass and radius compatible with those of the donor in IGR J17480–2446 we find that \( \tau_{TC} \) is much shorter of both the age of the cluster and the exchange interaction timescale \( \tau_{exc} \) calculated in the previous sections.

Finally, the eccentricity of binaries formed via tidal capture is known to dissipate on a timescale which is
much shorter than any other timescale considered in this work (McMillan et al. 1987), even when considering the possible initial chaotic state of the orbits (Mardling 1995a,b). This again favors the tidal capture scenario because it can easily explain the basically circular orbit observed.

### 3.3. Scenario III: Accretion Induced Collapse

Accretion induced collapse (AIC) has been invoked to solve some problems related with the fine tuning of the short lived wind fed and RLOF phase of IGR J17480–2446 (Patruno et al. 2012). In our simulations, however, we have demonstrated that the dynamical encounters are in principle sufficient to explain the observations, with the exception of the rather low magnetic dipole moment of the neutron star, under the assumption that the field decays via fluxoid expulsion from the neutron star core during the wind fed epoch.

The variation of the orbit generated by a quasi-spherical mass loss is given by:

$$a_{\text{fin}} - a_{\text{in}} = \frac{\Delta M}{M_1 + M_2 - 2\Delta M}$$  

where $a_{\text{in}}$ and $a_{\text{fin}}$ are the initial and final orbital separation once the collapse has occurred, $\Delta M \sim 0.2 M_\odot$ is the amount of mass lost in the collapse and $M_1 + M_2$ is the total mass of the binary prior the collapse. Since $M_1$ is constrained to be the Chandrasekhar mass of the white dwarf and $M_2$ cannot be much different than $\sim 1 M_\odot$ since the star belongs to the globular cluster, the expansion of the orbit would be of the order of $10 - 20\%$. This value (similar to the variation of the semi-major axis produced by a single encounter, see Section 3.1.1) has therefore little effect on the evolution of the binary.

The AIC scenario requires that the formation of the neutron star has happened not too early in the lifetime of the globular cluster, since otherwise the evolution of the binary would still be dominated by the dynamics in the globular cluster, and invoking the AIC scenario would thus be unnecessary. The mass transfer phase should therefore be relatively short and the initial white dwarf mass needs to be rather massive ($\gtrsim 1 M_\odot$) so that the donor star has enough material to bring the white dwarf above the Chandrasekhar limit. Furthermore the donor has to still preserve a mass of about $0.8 - 0.9 M_\odot$ to feed the neutron star in the currently observed RLOF epoch. The initial mass of the donor is thus required to be at least $1.0 - 1.3 M_\odot$ and the AIC must have happened when these kind of stars were still present in the cluster.

Furthermore, for the AIC to occur, the mass accretion rate from the donor star towards the white dwarf needs to be within a certain range such that hydrogen burning on the white dwarf is stable. Explosive ignition of the accreted matter would otherwise hardly allow any mass growth of the compact object since most of the mass would be expelled during the explosion (Townsley & Bildsten 2005, van den Heuvel 2011). The critical range of stable accretion weakly increases with the white dwarf mass, and reaches values of the order of $1 - 4 \times 10^{-7} M_\odot$ yr$^{-1}$ for a massive white dwarf of $1 - 1.2 M_\odot$. To have such large mass accretion rates a relatively massive donor is required (see e.g., Tauris et al. 2013) which again would conflict with the constraint that the binary has formed recently. These particular set of requirements imply that the formation scenario with an accretion induced collapse white dwarf is the most unlikely among the three explored in this work.

### 4. ROCHE LOBE OVERFLOW AND THE EFFECT OF CLOSE ENCOUNTERS

We now switch to the question of what happens to interacting binaries when a dynamical encounter occurs after a contact phase has already started. The effect of close encounters will indeed alter the orbital evolution of the binary and produce sudden shifts in location of the donor star. In essence, this can suddenly stop or trigger a RLOF phase.

Once the donor star has drifted sufficiently close to the neutron star, a Roche lobe overflow (RLOF) phase can start. Evolutionary sequences of LMXBs have been extensively explored in the literature (see for example Rappaport et al. 1982; Podsiadlowski et al. 2002). However, the evolutionary sequences of binaries perturbed by close encounters every $\sim 30$ Myr are likely to have a different outcome. Close encounters recur on a timescale which is much shorter than both typical nuclear and magnetic braking evolutionary timescales of low mass main-sequence and giant stars. The same holds if we compare with the timescale of gravitational radiation emission, which is one to two orders of magnitude longer. Furthermore, as we found in Section 3, the change in semi-major axis experienced at each encounter is of the order of 15% and it can be sufficient to detach the donor from its Roche lobe and switch off the accretion, or bring the donor star into contact (depending on the sign of the semi-major axis change) at an earlier stage than the typical evolutionary timescale. The Roche lobe size scales linearly with the orbital separation $R_\text{L} \propto a$ and therefore each encounter changes the Roche lobe by an amount proportional to the variation of the semi-major axis. It is also possible that the donor is already in RLOF before the next encounter occurs. The typical duration of non-resonating encounters lasts in general less than a few orbital periods, so that the variation of the Roche lobe size can be considered almost instantaneous. In this case the mass transfer rate is suddenly increased or halted, depending on the sign of $\dot{a}$.

If the star is already in (or close to) a RLOF phase, then a close encounter that shrinks the orbit would move the star off hydrostatic equilibrium in a very short time. Indeed the slope of the mass-radius relation for the Roche lobe $\zeta \approx \frac{M}{L}$ would be much larger than the slope of the same relation for the donor.

**Figure 7.** Tidal capture timescale for a $1.4 M_\odot$ neutron star and four different donors with radii spanning a range between 0.5 and 2$R_\odot$. The solid lines refer to a neutron star globular cluster core density of $n_{NS} = 10^5$ pc$^{-3}$, whereas the dashed lines to $n_{NS} = 10^6$ pc$^{-3}$. The horizontal dot-dashed red line marks the exchange timescale $t_{\text{exch}} \approx 10$ Gyr. The tidal capture timescale is substantially shorter than the exchange interaction timescale in all cases.
star ($\zeta_d$):
\[
\zeta_d = \frac{d \ln R_1}{d \ln m_2} \Rightarrow \zeta_d = \frac{d \ln R}{d \ln m_2}.
\] (9)

Therefore we do not follow this effect in detail since dynamical timescales need to be considered. We can anyway speculate that four scenarios are likely to appear:

- the encounter shrinks/widens the orbit of a detached system which remains detached
- the encounter widens the orbit of a contact systems and shuts down the mass transfer phase
- the encounter shrinks the orbit of a detached system and brings the donor into Roche lobe contact
- the encounter shrinks the orbit of a contact system and produces an enhancement of the mass transfer rate

The latter two possibilities are perhaps the most interesting as they might produce an abrupt increase of the mass transfer rate well in excess of the Eddington limit possibly leading to a common envelope (CE) phase or an ejection of the stellar envelope. If we assume that a certain fraction of envelope mass is lost in the encounter, then the orbital energy variation per encounter is of the order of (Ivanova 2011):
\[
\Delta E_{\text{orb}} = -\frac{G m_1 m_2}{2 a_{\text{in}}} + \frac{G m_1 m_{2,c}}{2 a_{\text{f}}} \quad (10)
\]

where $m_{2,c}$ is the donor mass after it has expelled (a fraction of) its envelope. The typical binding energy of the donor envelope is instead:
\[
E_{\text{bin}} = \frac{G m_2 m_{2,c}}{R} \quad (11)
\]

By taking as a typical orbital separation a value of 0.01–0.02 AU, a donor mass of 1 $M_\odot$ and an envelope mass of 0.1–0.5 $M_\odot$, then $\Delta E_{\text{orb}}$ and $E_{\text{bin}}$ are of the same order of magnitude ($\sim 10^{47}$–48 erg), meaning that an encounter can lead to the ejection of the entire stellar envelope.

The details of the unstable mass transfer leading to a common envelope phase is subject to more uncertainties, with the star that is expected to be suddenly brought out of hydrostatic equilibrium. A spiral-in phase can also set in, with the compact object merging with the stellar core (see Piddlesiowski 2001 for a discussion) possibly producing Thorne-Zytkow type objects (Thorne & Zytkow 1977).

Even if we do not follow such evolutionary phases in our calculations, it is important to highlight that such unstable binaries are expected to occur in large numbers because of the high rate of encounters and therefore might be common in massive and concentrated globular clusters like Terzan 5. The question on whether this process might be connected with the over-abundance of pulsars and X-ray binaries in concentrated and massive clusters cannot be addressed at this moment.

5. CONCLUSIONS

In this paper we have proposed a formation scenario for the peculiar accreting binary IGR J17480–2446 in the globular cluster Terzan 5. Our calculations show that the most likely scenario for the formation of IGR J17480–2446 is one involving a tidal capture of a star, which occurs on a timescale of 0.2–8 Gyr (depending on physical details of the donor star). This scenario can explain naturally the apparently young age of IGR J17480–2446, the currently orbital separation of the binary, its (nearly) circular orbit and the proximity of the orbital period to the bifurcation one. This scenario requires no fine tuning, differently from the other mechanisms considered in this work. This conclusion is also compatible with the earlier suggestion made by Patruno et al. (2012) that IGR J17480–2446 is not a primordial binary, since that scenario would be incompatible with the spin-up behavior of the system and would require fine tuning for the beginning of the RLOF phase.

Dynamical simulations suggest that IGR J17480–2446, as well as other binaries in the core of Terzan 5, have been strongly and constantly perturbed by close encounters occurring on average every $\approx 30$ Myr, which might have altered their normal evolution. These perturbations might induce “hiccups” in the accretion phase, with the RLOF suddenly switching on and off. This can happen only in dense environments like globular cluster cores. It remains to be assessed whether our evolutionary scenario correctly represents the observed X-ray source populations in globular cluster.

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