Neutron stars and millisecond pulsars in star clusters: implications for the diffuse $\gamma$-radiation from the Galactic Centre

Giacomo Fragione, Václav Pavlík, Sambaran Banerjee

1 Racah Institute for Physics, The Hebrew University, Jerusalem 91904, Israel
2 Astronomical Institute of the Charles University, V Holešovičkách 2, 180 00 Prague 8, Czech Republic
3 Observatory and Planetarium of Prague, Královská obora 233, 170 21 Prague 7, Czech Republic
4 Argelander-Institut für Astronomie (AIfA), Auf dem Hügel 71, 53121 Bonn, Germany
5 Helmholtz-Instituts für Strahlen- und Kernphysik (HISKP), Nussallee 14-16, 53115 Bonn, Germany

ABSTRACT

Globular clusters (GCs) are the ideal environment for the formation of neutron stars (NSs) and millisecond pulsars (MSPs). NSs origin and evolution provide a useful information on stellar dynamics and evolution in star clusters, and are among the most interesting astrophysical objects, being precursors of several high-energy phenomena such as gravitational waves and gamma-ray bursts. Due to a large velocity kick that they receive at birth, most of the NSs escape the local field, affecting the evolution and dynamics of their parent cluster. In this paper, we study the origin and dynamical evolution of NSs within GCs with different initial masses, metallicities and primordial binary fractions. We find that the radial profile of NSs is shaped by the BH content of the cluster, which partially quenches the NS segregation until most of the BHs are ejected from the system. Independently on the cluster mass and initial configuration, the NSs map the average stellar population, as their average radial distance is $\approx 60 - 80\%$ of the cluster half-mass radius. Finally, by assuming a recycling fraction of $f_{\text{rec}} = 0.1$ and an average MSP gamma-ray emission of $L_\gamma = 2 \times 10^{33}$ erg s$^{-1}$, we show that the typical gamma-ray emission from our GCs agrees with observations and supports the MSP origin of the gamma-ray excess signal observed by the Fermi-LAT telescope in the Galactic Centre.

Key words: stars: neutron – pulsars: general – Galaxy: kinematics and dynamics – gamma-rays: galaxies – gamma-rays: diffuse background – Galaxy: centre – galaxies: star clusters: general

1 INTRODUCTION

Globular clusters (GCs) are known to be the breeding grounds for the formation of neutron stars (NSs) and millisecond pulsars (MSPs). GCs host a large number of NSs that are the final product of the lifetime of stars with masses between $\approx 9 - 20 M_\odot$ (Hurley et al. 2000, 2002). NSs are observed in GCs mainly through their participation in interacting binary systems, either as low-mass X-ray binaries (LMXBs) or MSPs, with typical luminosities of $\approx 10^{33} - 10^{38}$ erg s$^{-1}$ in X- and gamma-rays (Ivanova et al. 2008). As a consequence of high densities in GCs, it has been observed that the abundance of these objects (per unit mass) is $\approx 100$ times higher than in the Galaxy as a whole (Katz 1975).

NS origin and evolution provide us with a useful information and constraints for our understanding of both stellar dynamics and evolution in star clusters. Even though hundreds of NSs are formed in a star cluster, most of them receive a velocity kick at birth whose magnitude is typically much larger than it would be required to escape from a GC (Davies & Hansen 1998; Hansen & Phinney 1997; Hobbs et al. 2005). Therefore, only a small fraction of NSs is finally retained in clusters. Trenti, Vesperini & Pasquato (2010) presented $N$-body simulations of star clusters with different primordial binary populations and mass profiles, and showed that the retention fraction of NSs and black holes (BHs) plays a role in determining the final properties of the cluster, e.g. the size of its core.
MSPs are believed to be "recycled" pulsars. This terminology comes from the most common and accepted pathway to form such objects, i.e. the spin up of a NS that accretes mass from a companion star in a binary system (Plimne & Kulkarni 1994). The accretion phase lasts few hundred Myrs, during which the system shines and can be observed in X-ray (Tauris et al. 2012). The formation of a MSP still remains a complex problem and a lot of physics intervenes in speeding up the NS, which has not yet been understood completely (Tauris 2011; Tauris et al. 2012).

A new attention to NSs and MSPs comes from the recent high-quality data (in the energy range from about 20 MeV to over 300 GeV) from the Large Area Telescope instrument on board the Fermi Gamma-Ray Space Telescope (Fermi-LAT). The Fermi data proved the presence of an extended (out to \(3 \text{kpc}\)) gamma-ray excess around the Galactic Centre, peaking at \(\approx 2 \text{GeV}\), with an approximately spherical density profile \(\propto r^{-2.4}\) (Abazajian et al. 2014; Calore et al. 2015). There is no clear understanding of the origin of such a gamma-ray excess, with dark matter annihilation and thousands of MSPs possible sources (Brandt & Kocsis 2015; Calore et al. 2015). In the latter scenario, Galactic GCs inspiralling towards the Galactic Centre due to dynamical friction are expected to deposit their population of MSPs which are then inherited by the Nuclear Star Cluster and contribute to the observed gamma-ray excess (Fragione, Antonini & Gnedin 2018).

In this paper, we reconsider the origin and evolution of NSs in GCs. We study the origin and dynamical evolution of the NS population of GCs by the means of direct N-body simulations performed with the state-of-the-art N-body evolution code NBody7 (Aarseth 2012). We consider different cluster masses, initial fractions of primordial binaries and metallicities (Banerjee 2017, 2018). Finally, we infer the typical population of MSPs in our models and discuss its implications for the MSP origin of the gamma-ray emission in the Galactic Centre.

Our paper is organized as follows. In Section 2, we describe our numerical models of star clusters. In Section 3, we discuss our results and show how the NS population is related to the stellar mass content of the cluster. In Section 4, we discuss the gamma-ray emission from MSPs in our clusters. In Section 5, we summarize our conclusions.

## 2 MODELS

In the presented work, we utilize direct N-body evolutionary models of star clusters with initial masses, \(M_{\text{ini}}\), ranging from \(3.0 \times 10^4 \, M_\odot\) to \(7.5 \times 10^4 \, M_\odot\) and the initial half-mass radius \(r_{\text{h,ini}} \approx 2 \, \text{pc}\). Stellar masses, \(m\), are sampled from the initial mass function (IMF, Kroupa 2001), given by

\[
\xi(m) = \begin{cases} 
    k_1 \left( \frac{m}{m_{\text{min}}} \right)^{-1.3} & m_{\text{min}} \leq m/M_\odot \leq 0.5 \\
    k_2 \left( \frac{0.5}{m_{0.5}} \right)^{-1.3} \left( \frac{m}{0.5} \right)^{-2.3} & 0.5 \leq m/M_\odot \leq 100
\end{cases},
\]

(1)

where \(k_1\) and \(k_2\) are the normalization factors and \(m_{\text{min}} = 0.08\). The initial binary fraction is defined as

\[
f_{\text{bin}} = \frac{N_{\text{bin}}}{N_{\text{bin}} + N_{\text{stat}}},
\]

(2)

where \(N_{\text{bin}}\) is the number of binaries and \(N_{\text{stat}}\) is the number of single stars in the cluster. In the models presented here, the overall primordial binary fraction is set to either \(f_{\text{bin}} = 0.0\) or \(\approx 0.05\). However, as elaborated in Banerjee (2018, see their Sec. 2), the initial binary fraction of the O-type stars, taken separately, is \(\approx 100\%\), to be consistent with the observed high binary fraction among O-type stars in young clusters and associations (see, e.g., Sana & Evans 2011). As discussed there, the O-type-stellar binaries are taken to initially follow the orbital-period distribution of Sana & Evans (2011) and a uniform mass-ratio distribution (an O-star is paired only with another O-star, as typically observed, and the pairing among the lower-mass stars is obtained separately; see below). The orbital periods of the non-O-star primordial binaries are taken to follow a Duquennoy & Mayor (1991) distribution that represents a dynamically-processed binary population (Kroupa 1995), and their mass-ratio distribution is also taken to be uniform. The initial binary eccentricities, \(e\), are drawn from a thermal distribution (Spitzer 1987), \(f_\epsilon(e) = 2e\). Such a scheme of including primordial binaries provides a reasonable compromise between the economy of computing and consistencies with observations (Banerjee 2018). The model parameters are provided in Tab. 1.

These long-term direct N-body computations, some of which are the ones presented in Banerjee (2017) and Banerjee (2018), are performed with NBody7 (Aarseth 2012). This code is a descendant of the widely-used NBody6 direct N-body evolution code (Aarseth 2003; Nitadori & Aarseth 2012). NBody7 uses the Algorithmic Regularization Chain (ARC; Mikkola & Tanikawa 1999; Mikkola & Merritt 2008) instead of the classic KS-Chain Regularization in NBody6 (Mikkola & Aarseth 1993; Aarseth 2003). This ensures a reliable and numerically stable treatment of multiple systems (subsystems) of arbitrary mass ratios, especially those involving one or more massive objects (e.g. BHs), which continue to form and dismantle dynamically in any dense environment. The implementation of ARC also allows the on-the-fly post-Newtonian (PN) treatment in subsystems of binary or triple BHs, when general-relativistic (GR) effects become important (Mikkola & Merritt 2008).

NBody7 otherwise utilizes similar numerical strategies as NBody6, i.e. a fourth-order Hermite integrator (Aarseth 2003) to accurately advance the trajectories of each member that is subjected to the resultant force from the rest of the bodies. To relax the tedious \(\propto N^6\) dependence in computing time, a neighbour-based scheme is applied for evaluating the force contributions (Nitadori & Aarseth 2012) at the shortest time intervals (the “irregular” force/steps). At longer time intervals (the “regular” force/steps), all members in the system are included in the force evaluation. Inexpensive (yet numerous) irregular forces are computed using (OMP) parallel processing in regular single-node workstation CPUs, while the much more expensive regular force evaluations are done on CUDA-enabled high-performance GPUs.\(^1\) Diverging Newtonian gravitational forces during close hyperbolic passages and in hard binaries are handled by two-body or KS regularization (Aarseth 2003). Higher-order and GR subsys-

\(^1\) Compute-Unified Device Architecture

\(^2\) All computations in this work are done on workstations equipped with quad-core AMD processors and NVIDIA’s Fermi and Kepler series GPUs.
In the models presented here, we used the single-star and binary-star evolution models (SSE, BSE) of Hurley et al. (2000, 2002) that are integrated in the BBDY7 code. That way, the dynamical evolution and interactions are computed in tandem with the nuclear evolution of individual members.

The SSE algorithm is parametrized by the body’s mass \( m \) and metallicity \( Z \), and it is able to describe the evolution in a mass range \( m \in (0.1, 100) M_\odot \), by default. In the computed models, however, the strict 100 \( M_\odot \) limit is relaxed due to adopting of an optimally-sampled IMF (Kroupa et al. 2013). Generally, the nuclear evolution is faster for stars of higher-mass and lower metallicity. The exact time until a main sequence star becomes a NS, however, also depends on whether it is in a binary or not because the BSE introduces additional physical processes, e.g. mass transfer, accretion, collisions etc.

The process of a final transformation from a giant star to a NS is usually accompanied by a type-II supernova (SN) explosion. As the supernova explosion is never perfectly symmetric, there is an excess of momentum of the ejecta in one direction. This excess of momentum is known as the supernova kick.

The evolution of the total mass bound to the cluster for all the models in Tab. 1. The models may be identified based on their binary fractions (solid lines for \( f_{\text{bin}} = 0 \) and dashed lines for \( f_{\text{bin}} = 0.05 \)) and initial masses (specified at \( t = 0 \) Gyr on the vertical axis). Different colours represent different initial metallicities \( Z \). From the bottom to the top: Models M30k0b and M30k5b (3.0 \( \times 10^4 \) \( M_\odot \)), models M50k0b and M50k5b (5.0 \( \times 10^4 \) \( M_\odot \)), and model M75k0b (7.5 \( \times 10^4 \) \( M_\odot \)).

**Table 1.** Parameters of the models used: GC mass \( (M_{\text{ini}}) \), half-mass radius \( (r_{h,\text{ini}}) \), primordial binary fraction \( (f_{\text{bin}}) \) and metallicity \( (Z) \). All models have the initial Plummer (1911) distribution.

| Model  | \( M_{\text{ini}} \) \( (M_\odot) \) | \( r_{h,\text{ini}} \) (pc) | \( f_{\text{bin}} \) | \( Z \) |
|--------|----------------|----------------|----------------|-------|
| M30k0b | 3.0 \( \times 10^4 \) | 2.0 | 0.00 | 0.001, 0.005, 0.02 |
| M30k5b | 3.0 \( \times 10^4 \) | 2.0 | 0.05 | 0.001, 0.005, 0.02 |
| M50k0b | 5.0 \( \times 10^4 \) | 2.0 | 0.00 | 0.001, 0.005, 0.02 |
| M50k5b | 5.0 \( \times 10^4 \) | 2.0 | 0.05 | 0.001, 0.005, 0.02 |
| M75k0b | 7.5 \( \times 10^4 \) | 2.0 | 0.00 | 0.001, 0.005 |

**Table 2.** The number of NSs in our simulations and the total mass of the clusters, both at 10 Gyr.

| Model  | \( Z \) | \( n_{\text{NS}} \) | \( M_{\text{tot}} \) \( (\times 10^4 M_\odot) \) |
|--------|-------|----------------|----------------|
| M30k0b | 0.001 | 28 | 0.41 |
|        | 0.005 | 35 | 0.74 |
| M30k5b | 0.001 | 44 | 0.79 |
|        | 0.005 | 47 | 0.96 |
|        | 0.002 | 32 | 0.68 |
| M50k0b | 0.001 | 77 | 1.45 |
|        | 0.005 | 75 | 1.80 |
|        | 0.002 | 54 | 2.14 |
| M50k5b | 0.001 | 74 | 1.42 |
|        | 0.005 | 69 | 1.48 |
|        | 0.002 | 50 | 1.66 |
| M75k0b | 0.001 | 110 | 2.70 |
|        | 0.005 | 128 | 3.08 |

The number of NSs in Table 2 is calculated for different initial metallicities \( Z \) and primordial binary fractions \( f_{\text{bin}} \). The number of NSs is calculated at 10 Gyr, both in the models with different initial masses \( M_{\text{ini}} \) and binary fractions \( f_{\text{bin}} \). The models may be identified based on their initial metallicities \( Z \), which are specified in Table 1.
Figure 2. Time evolution of the number of NSs and the average distance of NSs from the GC centre for models M30k0b (top-left), M30k5b (top-right), M50k0b (middle-left), M50k5b (middle-right) and M75k0b (bottom-centre). Upper panels: The total number of NSs bound to the cluster in our models (see Tab. 1) for different values of the stellar metallicity. Lower panels: Solid lines represent the mean distance from the GC centre of the bound NSs; each highlighted area is the distance range of all the NSs.
direction which gives a recoil velocity to the remnant, i.e. a velocity kick (Lyne & Lorimer 1994). The distribution of kicks is supposed to be Maxwellian with a dispersion of $\sigma \approx 190 \text{ km s}^{-1}$ (Hansen & Phinney 1997) or $\sigma \approx 300 \text{ km s}^{-1}$ as in Hobbs et al. (2005) observations. Based on the mass of a star before becoming a SN, the explosion can either form a NS or a BH. The latter could also receive a kick, however, its properties may be different (cf. Belczynski et al. 2008; Verbunt et al. 2017; Pavlík et al. 2018). Another way of forming a NS is via an electron-capture supernova (ECS; Podsiadlowski et al. 2004). The ECS-NSs would receive no kick at birth or only a very small one due to an asymmetry in neutrino emissions. Recent hydrodynamic studies of the ECS-NS formation also support very small natal kicks (Gessner & Janka 2018).

The NS production and evolution of the NS population in our models is presented in Fig. 2. In the top panels, we plot the total number of NSs in each cluster in time. In the low-metallicity realisations, remnants are produced at earlier times because of a lower mass limit for the stellar core collapse. Therefore, we observe a larger number of NSs at the beginning of those calculations.

The NSs which form during a type-II SN mostly leave the cluster shortly after their birth because the escape velocity from the modelled clusters is much lower than the kick velocity dispersion of the NSs, $\sigma$. The NSs that remain bound to the cluster are mainly produced via ECS. Note
that only in an environment comparable to a Nuclear Cluster, where the escape velocity is of the same order as \( \sigma \), the high-kick NSs could remain bound (see e.g. Banerjee 2017, 2018).

Although the bound NSs are, on average, heavier and remain more concentrated than regular stars, their mass segregation is also partly quenched due to a heating effect of the BHs. Initially, i.e. when the BH-engine is active, we can see an overall expansion of the NS population\(^3\) (bottom panels of Fig. 2). They begin to collapse back when the engine is weakened, i.e. when a majority of BHs is dynamically ejected. For a lower \( Z \), the BHs may become more massive and more numerous, resulting in higher energy deposition in the rest of the cluster members. Consequently, the expansion is faster and the re-collapse occurs later.

Fig. 3 illustrates the ratio of the average NSs distance from the GC centre and the half-mass radius, i.e. \( r_{\text{NS}}/r_{\text{bin}} \). As it has been discussed, the radial profile of the NSs depends on the BH cluster activity and dynamical ejection, which in turn depends on the metallicity. However, we find that the NS population always approximately "maps" the stellar population, in the sense that the ratio \( r_{\text{NS}}/r_{\star} \) decreases from nearly unity to \( \approx 0.6 - 0.8 \) in a few Gyrs in all the clusters, independently of the initial metallicity, binary fraction, and cluster mass. Exceptions to the overall behaviour are the solar-metallicity models with zero primordial binaries. In these models, the segregation of the NSs is stronger due to a weaker BH heating and also the lack of heating from the primordial binaries. However, \( f_{\text{bin}} = 0 \) is probably an idealization since all clusters would have been born with a non-negligible primordial-binary population (Marka & Kroupa 2012), which partially suppresses the NS segregation even when the BH heating is weak.

4 MILLISECOND PULSARS, GAMMA-RAY EMISSION AND THE GALACTIC CENTRE GAMMA-RAY EXCESS

MSPs are believed to be recycled pulsars, the end product of binary systems made up of a NS that accretes mass from a companion star (Phinney & Kulkarni 1994). In such binaries, the NS is spun up via accretion of mass and angular momentum from the secondary star, and reduces its magnetic field. The recycling phase lasts few hundred Myrs during which the binary system shines in X-ray and is observable first as a LMXB and then as an X-ray MSP (Tauris et al. 2012). Even if this standard formation scenario is usually thought to be the most likely path to form MSPs, a lot of physics intervening in speeding up the NS is still not known or understood completely (Tauris 2011; Tauris et al. 2012).

Recycling a NS requires a small orbital separation in the progenitor binary. Dense stellar environments may help forming tight binaries, either via direct collision with a giant, tidal capture or exchange encounters (see, e.g., Hut et al. 1992; Banerjee & Ghosh 2007). Fabian et al. (1975, 1983) first predicted that MSPs would be abundant in GCs due to a high rate of stellar dynamical encounters

\[
\Gamma \propto \frac{\rho_c^2 r_c^4}{\sigma_{\text{disp}}}.
\]

where \( \rho_c^2, r_c^3 \) and \( \sigma_{\text{disp}} \) are the core density, the core radius and the velocity dispersion, respectively. Recent measurements by Bahramian et al. (2013) confirmed that there is a correlation between the number of X-ray and radio sources in a given GC and its stellar dynamical encounter rate \( \Gamma \), while Verbunt & Freire (2014) showed instead that the typical encounter rate for a single binary plays a role in providing a good characterization of the differences between the pulsar populations in various GCs.

Despite the success in explaining the observed features of X-ray binaries and MSP, a lot of uncertainties still remain, e.g. the cluster’s IMF, the primordial binary population, the typical lifetime of binary progenitors of MSPs and, in particular, the retention fraction of NSs (Podsiadlowski et al. 2004; Ivanova et al. 2008; Verbunt & Freire 2014). Moreover, the physics of LMXBs is usually modelled with simplified assumptions, which only recently have been discussed in more detail by Tauris (2011) and Tauris et al. (2012).

Recently, new attention to MSPs has been brought up by the Fermi-LAT telescope\(^4\) which provided high-quality data in the energy range from 20 MeV to over 300 GeV. The data show a gamma-ray excess around the Galactic Centre. Its peak energy is at \( \approx 2 \) GeV, with an approximately spherical density profile decreasing as \( r^{-2.4} \) out to 3 kpc from the Galactic Centre (Abazajian et al. 2014; Calore et al. 2015). There is no clear understanding of the origin of such a gamma-ray excess, with dark matter annihilation and MSPs possible sources. While the first interpretation is challenged by a non-detection of the corresponding signal from dwarf spheroidal satellite galaxies of the Milky Way (Albert et al. 2017), the emission of thousands of unresolved MSPs seems to be the most promising explanation (Lee et al. 2015; Bartels et al. 2016; Ackermann et al. 2017). Brandt & Kocsis (2015) proposed that the population of MSPs was left in the inner regions of the Milky Way as a consequence of GCs migration and disruption due to dynamical friction.

Fragione, Antonini & Gnedin (2018) used the data from Hooper & Linden (2016) to derive a relation between the gamma-ray emission from GCs and their masses. They found that the gamma-ray emission from GCs, as measured by Fermi, is well described by the following log-linear relation

\[
\log(L_{\gamma}/M_{\text{GC}}) = 32.66 \pm 0.06 - (0.63 \pm 0.11) \log(M_{\text{GC}}),
\]

where \( L_{\gamma} \) is the gamma-ray emission of a GC and \( M_{\text{GC}} \) is its mass. Fig. 4 shows the ratio of the gamma-ray luminosity to the globular cluster mass, \( L_{\gamma}/M_{\text{GC}} \), as a function of the cluster mass (as in Fragione et al. 2018) and the inferred \( L_{\gamma}/M_{\text{GC}} \) of the GCs studied in this work. In deriving \( L_{\gamma}/M_{\text{GC}} \) for our models, we use the final mass of our evolved GCs and the final number of NSs as was found in our simulations (see Tab. 2). We also assume a recycling fraction, i.e. the number of NSs that have been spun up, of \( f_{\text{rec}} = 0.1 \) as found by Abbate et al. (2018) and an average MSP gamma-ray emission of \( L_{\gamma} = 2 \times 10^{33} \text{ erg s}^{-1} \) (Brandt & Kocsis 2015). We find that our GCs models are in a good agreement with the Fermi data.\(^3\) Stellar population expands as well.

\(^3\) Stellar population expands as well.

\(^4\) https://fermi.gsfc.nasa.gov/
agreement with Eq. (4). By using this equation and evolving the primordial GC population in the Milky Way potential (see also Fragione, Ginsburg & Kocsis 2018) and taking into account the MSP spin-down, Fragione et al. (2018) showed that the accumulated population of MSPs well reproduces both in intensity and spatial profile the gamma-ray excess observed by Fermi. Since our inferred $L_\gamma/M_{GC}$ are in a good agreement with Eq. (4), we conclude that our results support the MSP origin of the gamma-ray excess signal observed by Fermi in the Galactic Centre.

5 CONCLUSIONS

NSs are among the most interesting astrophysical objects, being precursors of a lot of high-energy phenomena, such as gravitational waves and gamma-ray bursts. GCs are the natural environment where hundreds of NSs can form and dynamically evolve. As a consequence of high stellar densities and low velocity dispersions, NSs can interact with single and binary stars in GCs more frequently than in any other environment, and form bound binary systems, where they are observed either as LMXBs or MSPs in X- and gamma-rays (Ivanova et al. 2008; Katz 1975; Verbunt & Freire 2014).

We studied the origin and dynamical evolution of NSs within GCs with different initial masses, metallicities and binary fractions. We found that even though hundreds of NSs are formed in a star cluster, most of them receive a velocity kick at birth such that they escape from their parent GC (Davies & Hansen 1998; Trenti et al. 2010). The radial profile of NSs is shaped by the BH content of the cluster, which partially quenches the NS segregation. However, independently on the cluster mass and initial configuration, the NSs reasonably map the average stellar population, as their average radial distance is $\approx 60 - 80\%$ of the cluster half-mass radius.

MSPs are believed to be recycled pulsars, where a NS spins up by accreting mass from a companion star in a binary system (Phinney & Kulkarni 1994; Tauris et al. 2012). A new attention to MSPs comes from the recent high-quality data by Fermi, which observed an extended gamma-ray emission around the Galactic Centre. One of the possible origin of the excess is the emission by thousands of MSPs, probably delivered by Galactic GCs that inspiralled onto the Galactic Centre due to dynamical friction (Brandt & Kocsis 2015; Fragione et al. 2018). By assuming a recycling fraction $f_{rec} = 0.1$ (Abbate et al. 2018) and an average MSP gamma-ray emission of $L_\gamma = 2 \times 10^{33}$ erg s$^{-1}$ (Brandt & Kocsis 2015), we computed the $L_\gamma/M_{GC}$ of the GCs studied in this work and found that our results support the MSP origin of the gamma-ray excess signal observed by Fermi in the Galactic Centre.

6 ACKNOWLEDGEMENTS

This research was partially supported by an ISF and an iCore grant. GF acknowledges support from a Lady Davis postdoctoral fellowship at the Hebrew University of Jerusalem. VP acknowledges support from the Charles University, grants GAUK-186216 and SVV-260441. SB is thankful to the computing team of the Argelander-Institut für As-
tronomie, University of Bonn, for their efficient maintenance of the workstations on which all the computations have been performed.

REFERENCES

Aarseth S. J., 2003, Gravitational N-Body Simulations
Aarseth S. J., 2012, MNRAS, 422, 841
Abazajian K. N., Canac N., Horiuchi S., Kaplinghat M., 2014, Phys. Rev. D, 90, 023526
Abbate F., Mastrobuono-Battisti A., Colpi M., Possenti A., Sippel A. C., Dotti M., 2018, MNRAS, 473, 927
Ackermann M., et al., 2017, ApJ, 840, 43
Albert A., et al., 2017, ApJ, 834, 110
Bahramian A., Heinke C. O., Sivakoff G. R., Gladstone J. C., 2013, ApJ, 766, 136
Banerjee S., 2017, MNRAS, 467, 524
Banerjee S., 2018, MNRAS, 473, 909
Banerjee S., Ghosh P., 2007, ApJ, 670, 1090
Bartels R., Krishnamurthy S., Weniger C., 2016, Phys. Rev. Lett., 116, 051102
Belczynski K., Kalogera V., Rasio F. A., Tamm R. E., Zelas A., Bulik T., Maccarone T. J., Ivanova N., 2008, ApJS, 174, 223
Brandt T. D., Kocsis B., 2015, ApJ, 812, 15
Calore F., Cholis I., McCabe C., Weniger C., 2015, Phys. Rev. D, 91, 063003
Davies M. B., Hansen B. M. S., 1998, MNRAS, 301, 15
Duquennoy A., Mayor M., 1991, A&A, 248, 485
Fabian A. C., Pringle J. E., Rees M. J., 1975, MNRAS, 172, 15
Fabian A. C., Pringle J. E., Verbunt F., Wade R. A., 1983, Nature, 301, 222
Fragione G., Antonini F., Gnedin O. Y., 2018, MNRAS, 475, 5313
Fragione G., Ginsburg I., Kocsis B., 2018, ApJ, 856, 92
Gessner A., Janka H.-T., 2018, ArXiv e-prints (arXiv:1802.05274)
Hansen B. M. S., Phinney E. S., 1997, MNRAS, 291, 569
Hobbs G., Lorimer D. R., Lyne A. G., Kramer M., 2005, MNRAS, 360, 974
Hooper D., Linden T., 2016, Journ. Cosm. Astrop. Phys., 8, 18
Hurley J. R., Pols O. R., Tout C. A., 2000, MNRAS, 315, 543
Hurley J. R., Tout C. A., Pols O. R., 2002, MNRAS, 329, 897
Hut P., McMillan S., Goodman J., Mateo M., Phinney E. S., Pryor C., Richer H. B., Verbunt F., Weinberg M., 1992, PASP, 104, 981
Ivanova N., Heinke C. O., Rasio F. A., Belczynski K., Fregeau J. M., 2008, MNRAS, 386, 553
Katz J. I., 1975, Nature, 253, 698
Kroupa P., 1995, MNRAS, 277, 1491
Kroupa P., 2001, MNRAS, 322, 231
Kroupa P., Weidner C., Pfennig-Altenburg J., Thies I., Dabringhausen J., Marks M., Maschberger T., 2013, The Stellar and Sub-Stellar Initial Mass Function of Simple and Composite Populations. p. 115
Lee S. K., Lisanti M., Safdi B. R., 2015, Journ. Cosm. Astrop. Phys., 5, 56

Lyne A. G., Lorimer D. R., 1994, Nature, 369, 127
Marks M., Kroupa P., 2012, A&A, 543, A8
Mikkola S., Aarseth S. J., 1993, Celestial Mechanics & Dynamical Astronomy, 57, 439
Mikkola S., Merritt D., 2008, The Astronomical Journal, 135, 2398
Mikkola S., Tanikawa K., 1999, Monthly Notices of the Royal Astronomical Society, 310, 745
Nitadori K., Aarseth S. J., 2012, Monthly Notices of the Royal Astronomical Society, 424, 545
Pavlík V., Jerábková T., Kroupa P., Baumgardt H., 2018, Manuscript submitted for publication in A&A.
Phinney E. S., Kulkarni S. R., 1994, ARA&A, 32, 591
Plummer H. C., 1911, MNRAS, 71, 460
Podsiadlowski P., Langer N., Poelarends A. J. T., Rappaport S., Heger A., Pfahl E., 2004, The Astrophysical Journal, 612, 1044
Podsiadlowski P., Langer N., Poelarends A. J. T., Rappaport S., Heger A., Pfahl E., 2004, ApJ, 612, 1044
Sana H., Evans C. J., 2011, in Neiner C., Wade G., Meynet G., Peters G., eds, Active OB Stars: Structure, Evolution, Mass Loss, and Critical Limits Vol. 272 of IAU Symposium, The multiplicity of massive stars. pp 474–485
Spitzer L., 1987, Dynamical evolution of globular clusters Tauris T. M., 2011, Evolution of compact binaries. Proceedings of a workshop held at Hotel San Martin, Viña del Mar, Chile 6-11 May 2011. Edited by Linda Schmidtobreck, Matthias R. Schreiber, and Claus Tappert. ASP Conference Proceedings. San Francisco, CA, 447, 285
Tauris T. M., Langer N., Kramer M., 2012, MNRAS, 425, 1601
Trenti M., Vesperini E., Pasquato M., 2010, ApJ, 708, 1598
Verbunt F., Freire P. C. C., 2014, A&A, 561, A11
Verbunt F., Igosheva A., Cator E., 2017, ArXiv e-prints