Short γ-ray bursts from binary neutron star mergers in globular clusters

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The first locations of short gamma-ray bursts (GRBs) in elliptical galaxies suggest they are produced by the mergers of double neutron star (DNS) binaries in old stellar populations. Globular clusters, where the extreme densities of very old stars in cluster cores create and exchange compact binaries efficiently, are a natural environment to produce merging NSs. They also allow some short GRBs to be offset from their host galaxies, as opposed to DNS systems formed from massive binary stars which appear to remain in galactic disks. Starting with a simple scaling from the first DNS observed in a galactic globular, which will produce a short GRB in ∼300My, we present numerical simulations which show that ∼10–30% of short GRBs may be produced in globular clusters vs. the much more numerous DNS mergers and short GRBs predicted for galactic disks. Reconciling the rates suggests the disk short GRBs are more beamed, perhaps by both the increased merger angular momentum from the DNS spin-orbit alignment (random for the DNS systems in globulars) and a larger magnetic field on the secondary NS.

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The origin of cosmic gamma-ray bursts, like most astronomical mysteries, required precise source positions and identification at other wavelengths for the first breakthroughs. After nearly 25 years, the so-called "long" GRBs ($\gtrsim$2-200sec), were located by coded aperture imaging of their hard X-ray emission which enabled more precise positions from their soft X-ray afterglows[1] and then optical counterparts[2] to be found. The optical identifications established them to be at cosmological distances. They are now understood to be due to relativistic jets produced in the core collapse of massive stars to form stellar mass black holes in certain "hyper" supernova events.[3] However, about a third of GRBs were previously recognized[4] to be distinctly different: both shorter duration ($\lesssim$0.2-2 sec) and harder spectra. The recently-launched *Swift* satellite[5] was designed to solve the origin of the short GRBs by rapid detection of their X-ray and/or optical afterglows to enable their identification.

The first of these short GRBs, GRB050509b, was detected and located precisely ($\lesssim 5''$) enough by *Swift*[6] to enable its plausible optical identification[7] with the halo of an elliptical galaxy at 1.12 Gpc distance. A second short burst, GRB0507024, was located precisely by *Swift*[8,9] with an optical counterpart detected at an offset of ~2.5kpc from the center of another elliptical (E2) galaxy at very similar redshift (z = 0.257) and hence distance.[10] Since elliptical galaxies have long ceased active star formation, this suggested[10] that short GRBs are associated with old stellar populations and likely due to the merger of two neutron stars or a neutron star (NS) and stellar black hole (BH) in a compact binary system as originally suggested for GRBs generally.[11] The offset position for GRB050509b at 40±13kpc from its elliptical galaxy G1[7] would previously be attributed[12] to the ejection of the progenitor compact binary from the galaxy by the kick(s) imparted to it by the supernova event(s) which created its constituent neutron star(s) or black hole. This implies a kick velocity $\lesssim$600 km s^{-1} to remain bound to the elliptical, and yet $\gtrsim$200 km s^{-1} to have its apogalacticon in the halo. However, this is inconsistent with it being like the Hulse-Taylor binary pulsar[13] or the six other DNS systems now known in our Galaxy that were produced from the evolution of a massive binary system[14,15] since recent analysis[16] shows these are all likely low-kick velocity ($\lesssim$50 km s^{-1}) systems and thus are expected to remain within the central potential of their parent galaxies. Thus short GRBs from spiral or star formation galaxies, where massive binary evolution is producing DNS systems, are expected in their disks. Since the third short GRB located by *Swift*[17] is also associated with an elliptical, an alternative origin for their DNS progenitors is suggested.

We suggest instead that short GRBs are at least partly produced by DNS systems which formed in globular cores by exchange interactions of NSs into previously formed compact binaries containing a NS and low mass secondary. Subsequent mergers of these dynamically formed DNS compact binaries produced the short GRBs located by *Swift*. There is direct evidence that DNS systems form by dynamical interactions in globular clusters: the millisecond pulsar M15-C with a NS binary companion in the core collapsed globular cluster M15 in our Galaxy[18] must have formed within its ~100 My spindown age and then was scattered out of the cluster core by a NS exchange interaction[19] with a cluster low mass X-ray binary (LMXB) to produce a DNS with present eccentricity e = 0.68 and binary period P = 0.33d. We demonstrate this formation scenario, and find that significantly more DNS systems are produced by NSs in core collapsed globular clusters (like M15) by the exchange of a NS for the lower mass secondaries in quiescent low mass X-ray binary (qLMXB) or millisecond pulsar (MSP) binary systems in the cluster cores. A previous scenario[20] for long GRBs from globular clusters, brought to our attention after final submission of this paper, invoked NSs "smothered" in stellar merger collisions to form BHs (for which cross sections remain unknown) but produced comparable rates to our detailed results for re-exchange production of DNS systems.

Recent *Chandra* and *HST* observations[21,22] have shown that MSPs in globular cluster cores do indeed undergo subsequent encounters to re-exchange their evolved low mass secondaries for a main sequence (MS) star, which is not found or expected[14] for isolated evolution from a LMXB or qLMXB. The 30ms spin period of the M15-C pulsar implies it did not complete its spinup (90% of MSPs in globulars have shorter periods[23]), so that its original companion, as a LMXB, was thus a $\sim$0.4–0.7$M_\odot$ MS star (most probable in the core) that was exchanged for a cluster NS, in many cases another MSP. The re-exchange formation model developed here can operate with a wide range of original secondaries (most often $\sim$0.05–0.2$M_\odot$ He white dwarfs).

Given the existence of M15-C, can the globular cluster populations of elliptical galaxies plausibly contain enough DNS systems to account for a significant fraction of the short GRB rate? The answer is yes. We start with the conservative assumption that each L_* galaxy contains a globular cluster system with 10^3 globulars (typical for L_* ellipticals) and that the number density of such galaxies is $\sim$0.01 Mpc^{-3} as determined[24] from 2MASS and 2dF galaxy counts, yielding a globular cluster space density $n_{GC} \sim 10$Mpc^{-3}. Then, using the "local rate" of observed short GRBs derived by Schmidt[25] as $R_{GRB} \sim 0.08$ Gpc^{-3} yr^{-1}, the "observed" fractional number per globular of DNS systems like M15-C, with its $\tau_{merge} \sim$300My merger time, would need be $f_{obs} = R_{GRB}\tau_{merge}/n_{GC} \sim 2.4 \times 10^{-3}$ to account for short GRBs. Correcting for the short GRB beaming factor of $\sim$30-50 inferred[10] for (only!) one short GRB, GRB050724, multiplies the observed value for the total number of short GRB progenitors. However this is partly offset by the pulsar beaming factor for MSPs,[26] $B_{MSP} \gtrsim 2$, where the lower limit applies if DNS systems contain at least one MSP. Thus the net beaming factor $B_{DNS} = B_{GRB}/B_{MSP} \gtrsim 15$ and the total number of DNS systems needed per globular is $f_{DNS} = f_{obs}\ B_{DNS} \lesssim 0.04$. Thus short GRBs could then arise from a population of DNS systems in globular clusters around L_* galaxies if they were produced within ~4% of its globulars. If, as we show below, this largely arises in the ~20% of globulars that have undergone core collapse,[27] then DNS systems are required in ~20% of the post core collapse (PCC) clusters, which would suggest another ~7 of the ~40 PCC globulars in the Galaxy should contain a M15-C-like system. This is consistent with currently incomplete globular cluster surveys for pulsars which already find 8 MSPs in binaries with large eccentricities,[23] many of which could have NS companions.

Motivated by this simple scaling, we have conducted numerical scattering experiments using the `scatter3` and `sigma3` programs[28] in the `Starlab` software environment[29] to compute cross sections for the formation of DNS systems with merger times less than the age of the universe, as well as the distributions of their emergent velocities, retention probabilities, final periods and eccentricities. Each experiment consists of a three-body scattering between a target binary containing a $1.4M_\odot$ NS primary and a MS or helium WD secondary, with parameters chosen to represent the MSP, qLMXB and (relatively rare) LMXB targets that a lone NS in the cluster might encounter. Our target outcome is an exchange interaction leading to the formation of a DNS binary with a merger time smaller than a typical cluster age, ~ 10 Gyr.

We adopt the following parameters for our experiments: MS secondaries are assumed to have masses of 0.2, 0.4, or $0.8M_\odot$, while the WD masses are 0.05 or $0.2M_\odot$. The initial binary orbits have periods ranging from 0.01 to 100d (as appropriate for WD or MS secondaries) and zero eccentricity, as observed (very nearly) for most MSPs (and as expected for their progenitor qLMXBs). Incoming NS velocities are 10 km s^{-1}, a typical cluster velocity dispersion. We include the possibility of stellar collisions during the interaction. The secondary radii are the zero-age MS radii for the MS stars, and 0.03 and $0.018\,R_\odot$ for the 0.05 and $0.2M_\odot$ WD secondaries, respectively. NS radii are taken to be 15 km. We performed a total of $\sim 3 \times 10^6$ simulations, leading to statistical errors in our derived cross sections of $\lesssim 3\%$.

The results are quite remarkable: M15-C systems could be produced with cross sections that are comparable (~0.8 AU^2) over target binary periods P_b ~0.1–1d (Figure 1). Even more striking is the range of output DNS periods (P_b) and eccentricities (e) produced by these exchange encounters (Figure 2). For the $0.4M_\odot$ MS secondary case appropriate to M15-C, and the exchange interaction randomly distributed between $t = 0$ and $t =$

10^{10} years, the orbital evolution due to the emission of gravitational wave radiation is subsequently followed for each of the DNS systems produced until the current age of the Galaxy of 10^{10} years. The star indicates the observed position of the binary pulsar M15-C and is "predicted" by the distribution of survivors (heavy dots).

With the cross sections in Fig 1 we can estimate the number of DNS systems produced per globular. We assume that the orbital period distribution of progenitor systems is similar to that observed for MSPs in Galactic globular clusters,[23] resulting in an average cross section of $\sigma \simeq 0.8\,\mathrm{AU}^2$. We note that this greatly exceeds the area of the target binary orbit due to gravitational focusing at low encounter velocity ($\sim$10 km s^{-1}). The instantaneous formation rate of DNS binaries which will merge within 10 Gyr is then given by $\Gamma = N_{\rm pr} n \sigma v$, where $N_{\rm pr}$ is the number of potential progenitor systems in a cluster with mean neutron star number density n and velocity dispersion v. After substitution and scaling to parameters typical of globular clusters, we obtain

$$\Gamma_{\rm DNS} \simeq 4 \left(\frac{n}{[10^6\,\mathrm{pc}^{-3}]}\right) \left(\frac{\sigma}{[0.8\,\mathrm{AU}^2]}\right) \left(\frac{v}{[10\,\mathrm{kms}^{-1}]}\right) \left(\frac{N_{\rm pr}}{[20]}\right)\ \mathrm{Gyr}^{-1}\,\mathrm{globular}^{-1}\,, \qquad (1)$$

where, as discussed below, we normalize to a neutron star density of $n \sim 10^6\,\mathrm{pc}^{-3}$ and a total of $N_{\rm pr} = 20$ progenitor binaries containing a NS primary. The latter figure is estimated from the population of target LMXBs ($\sim$0.05), qLMXBs ($\sim$1) and MSPs ($\sim$10) per cluster, as derived from *Chandra* studies of (primarily) non-core-collapse but high central density clusters,[30] but increased by a factor of 2 for the expected production during core collapse of additional target LMXBs, MSP-WD and MSP-MS systems.

The quantity Γ_{DNS} varies dramatically over a cluster's evolutionary lifetime, rising sharply around the time of core collapse. Assuming a 10% neutron-star retention fraction,[31] we estimate that the Galaxy's "non-core-collapse" clusters have $n \sim 10^2 - 10^4\,\mathrm{pc}^{-3}$, while models for core-collapse clusters[32] predict $n \gg 10^6\,\mathrm{pc}^{-3}$. The cluster central velocity dispersion v depends only weakly on the state of the core,[32] scaling as $n^{0.05}$. As a result, during the homologous late stages of core collapse the central density n scales roughly as $\tau^{-1.2}$, where $\tau = t_{cc} - t$ is the time remaining until collapse, and the total number of DNS systems produced in the cluster, $N_{DNS} = \int \Gamma_{DNS}\, dt$, is dominated by the behavior near $\tau = 0$. Thus post-core-collapse (PCC) clusters, $\sim$20% of the total in the Galaxy,[27] would dominate the overall production of DNS binaries in globulars.

We use the M15 simulation data of Dull et al.[32] to resolve the formal singularity at

$\tau = 0$, and find that

$$\int_{t_{cc}-\tau_0}^{0} n(t)\,dt \;\approx\; 20 n_0 \tau_0\,, \tag{2}$$

where τ_0 is the time remaining until core collapse from a state with central density $n_0 = n(t_{cc} - \tau_0)$. The dependence of n on τ makes the precise instant at which this expression is evaluated relatively unimportant. We choose $n_0 = 10^6\,\mathrm{pc}^{-3}$, corresponding to $\tau_0 \sim 100 t_{rc} \sim 100$Myr for parameters appropriate to M15. The behavior of clusters during the PCC phase remains poorly understood but simulations indicate that the re-expansion is significantly slower than the collapse, and may include a series of nonlinear core oscillations. Thus we expect that the post-collapse phase will contribute at least as much to N_{DNS} as did the collapse; each recollapse will contribute roughly as much again. Weighting the cross sections of the DNS binaries with the observed orbital period distribution for MSPs in globulars,[23] since they dominate the DNS formation, we then estimate the total number of merging DNS binaries *per PCC cluster* as

$$N_{\rm DNS} \simeq 12 \left(\frac{\sigma}{[0.8 \mathrm{AU}^2]}\right) \left(\frac{v}{[10 \mathrm{kms}^{-1}]}\right) \left(\frac{N_{\rm pr}}{[20]}\right) \left(\frac{\tau_0}{[100\,\mathrm{Myr}]}\right) . \tag{3}$$

The coefficient 12 in Eq. (3) comes from $\sim$ 25% of the progenitors scattering directly into merging orbits, and a further $\sim$ 35% forming wider DNS systems that harden into merging orbits following a subsequent interaction during the core-collapse phase. We note that ∼10% of these systems will stem from (q)LMXBs and hence should be comparable to M15-C. The remainder, descended from MSPs, will be wider and more eccentric.

Thus, combining the two populations (qLMXBs/LMXBs and MSPs), ignoring the small differences in donor mass in qLMXBs and LMXBs, we derive a total of ∼12 DNS binaries per core-collapse cluster, or $\sim$ 480 DNS systems in the Galactic system of ∼40 PCC globulars formed over the age of the Galaxy. Some 400 of these have already merged due to the emission of gravitational waves (we estimate that in the last 1 Gyr ∼40 systems have merged), and ∼80 survive today (but will merge within a Hubble time, T_h). The majority of DNS systems are expected to remain in the globular cluster, as the exchange encounters tend to induce only a small recoil velocity on the binary pulsar. Only the LMXBs have significant (∼40%) ejection of DNS pulsars into the Galactic disk and halo, as suggested for M15-C.[19] Our derived total of ∼80 DNS systems surviving in the globular cluster system of the Galaxy (i.e., ∼2 per PCC globular) that will merge within T_h and produce short GRBs is $\sim 10\times$ larger than our simple scaling rate from M15-C alone. The difference comes from the fact that M15-C itself has a shorter than average merger time; our calculations now sample the entire distribution of merger times.

The derived DNS merger rate in the Galaxy of 40 per Gyr in 200 (total) globular clusters implies, for the same scalings to globular clusters in external galaxies, ~2 DNS mergers per year per Gpc^3. With the estimated short GRB beaming factor[10] B_{GRB}, this gives an observable GRB rate of ~0.07 Gpc^{-3} yr^{-1}, or roughly the Schmidt rate[25] but a factor of ~1.5–100 below the rates (with large uncertainties) recently obtained by Guetta and Piran,[33] for DNS production tied to the star formation rate. Given the large uncertainties in short GRB beaming factors, short GRB rates, and the details of core collapse (e.g., core collapse oscillations could increase our rates by factors $\gtrsim$2), and the additional DNS production from cluster primordial binaries containing NSs (most NSs retained in the cluster are likely in binaries), we conclude that perhaps ~10–30% of short GRBs are from DNS mergers in globulars.

Our DNS merger rate in globulars in the Galaxy of ~400 in 10^{10} years or ~0.04 Myr^{-1} yields a detection rate for ground based gravitational wave antennas that is $\gtrsim$200× smaller than the rates summarized[15,33] for DNS mergers in high mass binaries in the Galactic disk. Either these high mass progenitor rates for DNS production in the disk have been significantly overestimated, or most do not produce short GRBs, or their beaming angles are much smaller. We note that the NS population in globulars is likely dominated by recycled pulsars with low magnetic fields (B $\sim 10^{8-9}$ Gauss) whereas in the disk DNS systems the second-born NS, with no recycling, will have B $\sim 10^{12-14}$ Gauss. Although this B field is inconsiquential for the merger, it may launch a magnetically driven jet with smaller beaming angles. Combined with the randomly aligned spin-orbital angular momenta of DNS systems in globulars vs. the aligned spin-orbit vectors for disk systems, disk short GRBs might have beaming angles $\gtrsim$10× smaller to reconcile the rates.

The recent discovery of an interstellar medium (ISM) with density $n_{ISM} \sim 0.1$ cm^{-3} in the globular cluster 47 Tucanae[34] from the variable dispersion measure of its radio-detected MSPs is consistent with the ISM density deduced[10] for GRB050724. Globular clusters that have just traversed their host galaxy disks will have lower ISM densities, so that fainter afterglows are expected for some short GRBs, such as appears to be the case (given the non-detection) for GRB050509b.[6]

Finally, the short GRB050709 discovered with HETE[35] was followed by a faint, soft and delayed (~150s) X-ray flare which may point to a different origin. Mergers of BH-NS binaries may disrupt the NS and produce a "delayed" short GRB, whereas the lack of direct evidence for stellar mass BHs in globulars restricts the sample to NS-NS mergers. Indeed GRB050709 is reported[10] to be associated with a star formation galaxy and so is more plausibly a DNS merger from a massive binary although of course its host galaxy also presumably includes globular clusters. Thus short GRBs plausibly arise from two populations, as suggested on other grounds[33]: DNS or NS-BH mergers from high mass systems in star-forming disks with smaller beaming and DNS mergers from dynamically formed systems in globulars. The latter may be confirmed by further identifications with ellipticals or locations in host galaxy halos; the globular clusters themselves are too faint for detection with magnitudes V $\gtrsim$29 even at z $\sim$0.1.

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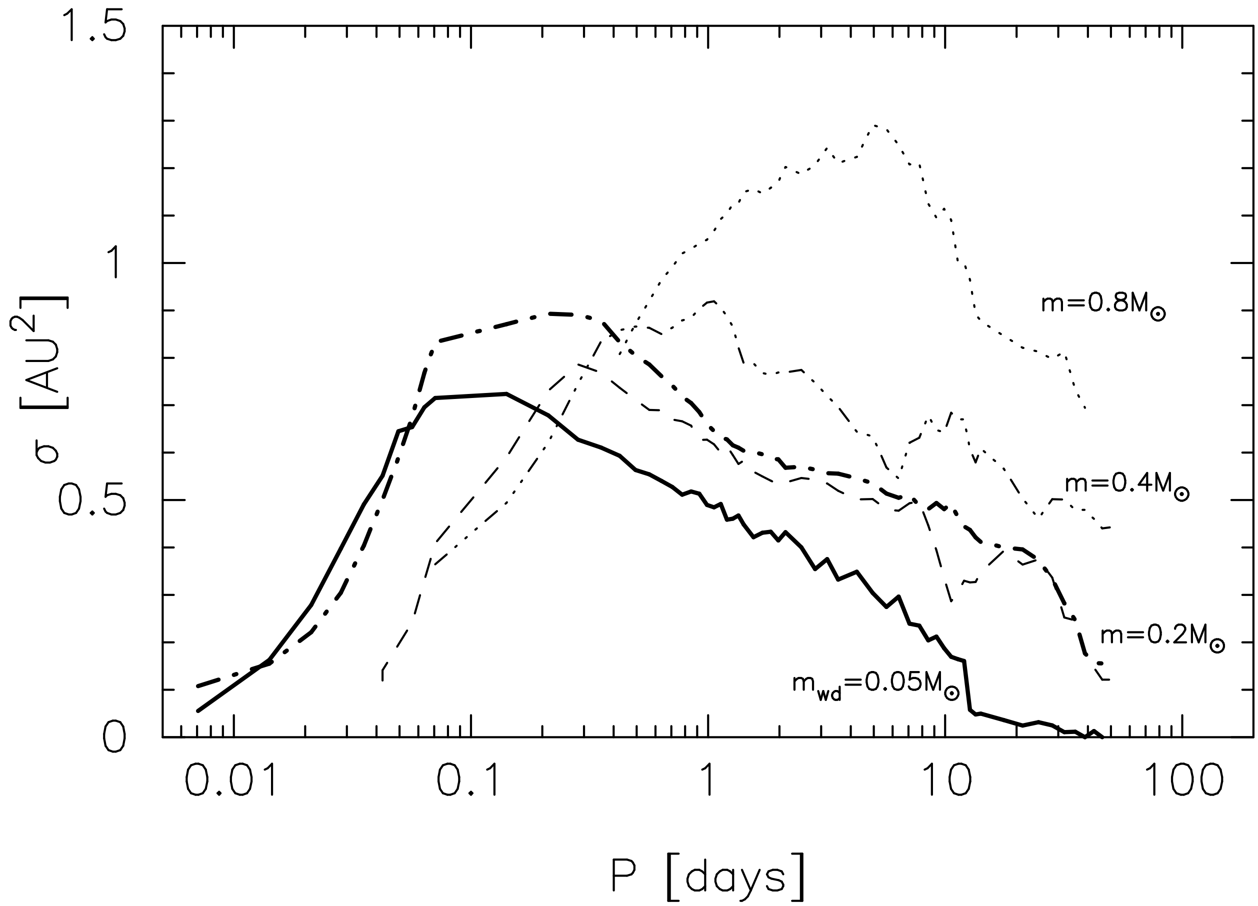

Figure 1. Cross sections for DNS production by exchange of low mass secondaries (in MSPs or LMXBs) with mass indicated for a NS. The $0.05M_\odot$ and $0.2M_\odot$ secondaries are calculated for He-WD mass-radius models and shown as the heavy curves, whereas the remaining $\gtrsim 0.2M_\odot$ cases are for main sequence stars. Target binary periods span the range shown. Corresponding compact binaries represented as actual "targets" are: LMXBs, with MS secondaries and masses $\gtrsim 0.2\ M_\odot$; qLMXBs, with (typically) $0.05M_\odot$ or $0.2M_\odot$WD or $0.2M_\odot$ main sequence secondaries; and MSPs, with $0.05M_\odot$ or $0.2M_\odot$ WD secondaries. The cross sections are comparable ($\sim$0.8 AU^2) over the distribution of target orbital periods (mostly $\sim$0.1–1d) of MSPs[23] or LMXBs in globulars. Total DNS numbers were derived from these cross sections, NS densities and number of progenitor binary systems for clusters near core collapse (see text).

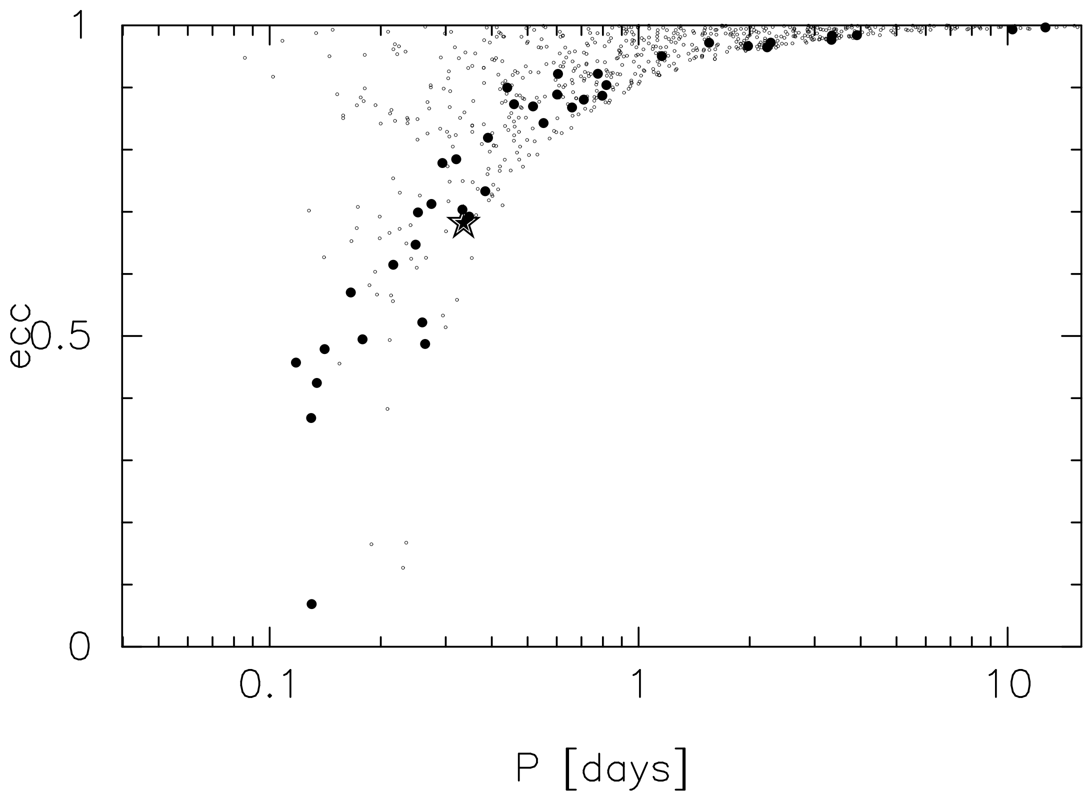

Figure 2. Binary period vs. eccentricity for DNS systems formed by NS exchange into LMXBs with 0.4$M_\odot$ secondaries. Only DNS binaries produced with merger times $\lesssim$10 Gy are plotted. Each "heavy" point marks a binary that has survived until today but will merge within a Hubble time, whereas the initially created DNS systems are marked by the small dots (most of which have merged). The **Star** marks the parameters for the M15-C system, showing that it indeed could be produced by an exchange encounter of a field NS with an LMXB (or qLMXB) containing a NS and 0.4$M_\odot$ secondary.