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

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Observations by the Swift gamma-ray-burst (GRB) mission located short GRBs in (or near) elliptical galaxies, that are no longer active in star formation. This suggested that short GRBs are produced when neutron stars (NSs) merge with other NSs or with black holes (BHs). However, the spatial offset of some short GRBs from their host galaxies is not consistent with double-neutron-star (DNS) systems formed from massive binary stars, which appear to remain in galactic disks. Instead, short GRBs may arise from NS mergers in compact binary systems that are naturally produced in globular clusters, in which extreme densities of very old stars can create and exchange compact binaries efficiently. Here we present a simple scaling from the DNS binary observed in the globular cluster M15 in our own Galaxy to the numbers expected for globular clusters around galaxies generally. We present numerical simulations that demonstrate that DNS production in globular clusters may account for ~10–30% of the observed short GRBs. The much more numerous DNS merger rates predicted for galactic disks suggests their associated short GRBs are significantly more beamed, perhaps by the aligned spins and greater magnetic field of their secondary NSs.

The origin of cosmic GRBs, like most astronomical mysteries, required precise source positions and identification at other wavelengths to enable the first breakthroughs. After nearly 25 years, the so-called 'long' GRBs ($\gtrsim 2-200$ s) 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 their 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 BHs in certain 'hyper' supernova events[3]. However, about a third of GRBs were previously recognized[4] to be distinctly different, with both shorter duration ($\lesssim 0.2-2$ s) and harder spectra. The 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 ($\lesssim 5$ arc seconds) 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 ~2.5 kpc from the centre of another elliptical (E2) galaxy at very similar redshift ($z = 0.257$) and hence distance[10]. As elliptical galaxies have long ceased active star formation, this suggested[10] that short GRBs are associated with old stellar populations and probably due to the merger of two NSs or a NS and stellar BH in a compact binary system as originally suggested for GRBs generally[11]. The offset position for GRB050509b at 40 ± 13 kpc from its elliptical galaxy G1 (ref. 7) would have been previously 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) that created its constituent NS(s) or BH. 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], as analysis[16] shows, these are all probably low-kick velocity ($\lesssim 50$ km s^{-1}) systems and thus are expected to remain within the central potential of their parent galaxies. Thus,

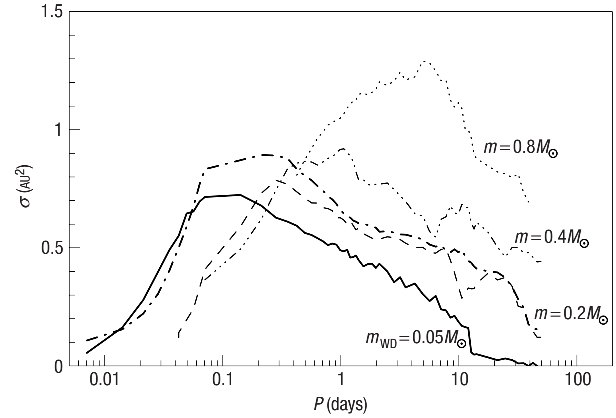

Figure 1 Cross-sections calculated for an incoming NS to exchange into a cluster compact binary composed of a NS and a secondary with masses indicated. The $0.05M_\odot$ and $0.2M_\odot$ secondaries are calculated for helium WD mass–radius models and are shown as the bold curves, whereas the remaining $\gtrsim 0.2M_\odot$ cases are for MS stars. Target binary periods span the range shown. Corresponding compact binaries represented as actual 'targets' are: LMXBs, with MS secondaries and masses $\gtrsim 0.2M_\odot$; qLMXBs, with (typically) $0.05M_\odot$ or $0.2M_\odot$ WD or (in some cases) $0.2M_\odot$ MS secondaries; and MSPs, with $0.05M_\odot$ or $0.2M_\odot$ WD secondaries. The cross-sections are comparable (~ 0.8 AU^2) when weighted over the distribution of orbital periods (mostly $\sim 0.3-1$ d) of MSPs in globulars[23], which are similar to their progenitor LMXB and qLMXB period distributions. Total DNS numbers were derived from these cross-sections, NS densities, and the number of progenitor binary systems for clusters near core collapse (see text).

short GRBs from spiral or star-formation galaxies, where massive binary evolution is producing DNS systems, are expected in their disks. As the third short GRB located by Swift[17] is also associated with an elliptical, an alternative origin for their DNS progenitors is suggested.

We propose instead that short GRBs are at least partly produced by DNS systems that 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 $\sim$100 Myr spindown age before being 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 $P = 0.33$ d. 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.

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 30 ms 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 mass $m \sim 0.4$–$0.7M_\odot$ 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 ~ 0.05–$0.2M_\odot$ He white dwarfs (WDs)).

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 ~ 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[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 merger time $\tau_{merge} \sim 300$ Myr, would need to 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 $\sim$4% of its globulars. If, as we show below, this largely arises in the $\sim$20% of globulars that have undergone core collapse[27], then DNS systems are required in $\sim$20% of the post-core-collapse (PCC) clusters, which would suggest around another seven of the $\sim$40 PCC globulars in the Galaxy should contain a M15-C-like system. This is consistent with currently incomplete globular-cluster surveys for pulsars that already find eight 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, $\sim$10 Gyr.

We adopt the following parameters for our experiments: MS secondaries are assumed to have masses of 0.2, 0.4 or $0.8M_\odot$, whereas the WD masses are 0.05 or $0.2M_\odot$. The initial binary orbits have periods ranging from 0.01 to 100 d (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 $0.018R_\odot$ 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%.

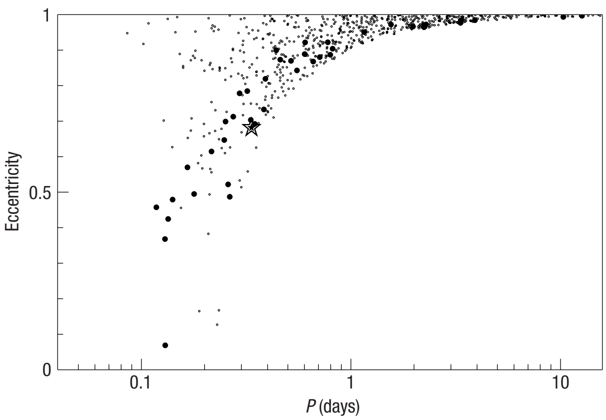

Figure 2 Distribution of binary period versus eccentricity for DNS systems formed by NS exchange into LMXBs with $0.4M_\odot$ secondaries. Only DNS binaries produced with merger times $\lesssim$10 Gy are plotted. Each 'bold' point marks a binary that has survived until today but will merge within a Hubble 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 could indeed be produced by an exchange encounter of a field NS with an LMXB (or qLMXB) containing a NS and $0.4M_\odot$ secondary.

The results are quite remarkable: M15-C systems could be produced with cross-sections that are comparable ($\sim$0.8 AU^2) over target binary periods $P \sim 0.1$–1 d (Fig. 1). Even more striking is the range of output DNS periods and eccentricities produced by these exchange encounters (Fig. 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 owing 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 (bold 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 $\sigma \simeq 0.8$ 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 that 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 NS number density n and velocity dispersion v. After substitution and scaling to parameters typical of globular clusters, we obtain

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

where, as discussed below, we normalize equation (1) to a NS density of $n \sim 10^6$ 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 two for the expected production during core collapse of additional target LMXBs, MSP-WD and MSP-MS systems.

The quantity $\Gamma_{\rm DNS}$ varies markedly over a cluster's evolutionary lifetime, rising sharply around the time of core collapse. Assuming a 10% NS retention fraction[31], we estimate that the Galaxy's 'non-core-collapse' clusters have $n \sim 10^2$–10^4 pc^{-3}, whereas models for core-collapse clusters[32] predict $n \gg 10^6$ 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 $\tau = t_{\rm cc} - t$ is the time remaining until collapse ($t_{\rm cc}$ is the time of core collapse), and the total number of DNS systems produced in the cluster, $N_{\rm DNS} = \int \Gamma_{\rm DNS}\, {\rm d}t$, is dominated by the behaviour near $\tau = 0$. Thus, PCC clusters, $\sim$20% of the total in the Galaxy[27], would dominate the overall production of DNS binaries in globulars.

We use M15 simulation data[32] to resolve the formal singularity at $\tau = 0$, and find that

$$\int_{t_{\rm cc}-\tau_0}^{0} n(t)\,{\rm d}t \approx 20 n_0 \tau_0, \quad (2)$$

where τ_0 is the time remaining until core collapse from a state with central density $n_0 = n(t_{\rm cc} - \tau_0)$. The dependence of n on τ makes the precise instant at which equation (2) is evaluated relatively unimportant. We choose $n_0 = 10^6$ pc^{-3}, corresponding to $\tau_0 \sim 100 t_{\rm rc} \sim 100$ Myr for the core relaxation time, $t_{\rm rc}$, appropriate to M15. The behaviour 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 $N_{\rm DNS}$ 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], as they dominate the DNS formation, we then estimate the total number of merging DNS binaries per PCC cluster as

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

The coefficient 12 in equation (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 $\sim$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) and ignoring the small differences in donor mass in qLMXBs and LMXBs, we derive a total of $\sim$12 DNS binaries per core-collapse cluster, or $\sim$480 DNS systems in the Galactic system of $\sim$40 PCC globulars formed over the age of the Galaxy. Some 400 of these have already merged owing to the emission of gravitational waves (we estimate that in the last 1 Gyr $\sim$40 systems have merged), and $\sim$80 survive today (but will merge within a Hubble time, $T_{\rm h}$). 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 ($\sim$40%) ejection of DNS pulsars into the Galactic disk and halo, as suggested for M15-C[19]. Our derived total of $\sim$80 DNS systems surviving in the globular-cluster system of the Galaxy (that is, about two per PCC globular) that will merge within $T_{\rm h}$ 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, around two DNS mergers per year per Gpc^3. With the estimated short GRB beaming factor[10] B_{GRB}, this gives an observable GRB rate of $\sim 0.07\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$, or roughly the Schmidt rate[25] but a factor of ∼1.5–100 below the rates (with large uncertainties) 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 (for example, 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 probably 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 $\sim 0.04\ \mathrm{Myr}^{-1}$ yields a detection rate for ground-based gravitational-wave antennas that is $\gtrsim 200\times$ 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 probably dominated by recycled pulsars with low magnetic fields ($B \sim 10^{8-9}$ G), whereas in the disk DNS systems the second-born NS, with no recycling, will have $B \sim 10^{12-14}$ G. Although this B field cannot prevent 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 versus the aligned spin–orbit vectors for disk systems, disk short GRBs might have beaming angles $\gtrsim 10\times$ smaller to reconcile the rates.

The discovery of an interstellar medium (ISM) with density $n_{\mathrm{ISM}} \sim 0.1\ \mathrm{cm}^{-3}$ 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 galaxies will have lower ISM densities, so that fainter afterglows are expected for some short GRBs, such as appears to be the case (given the lack of optical detection) for GRB050509b[6].

Finally, the short GRB050709 discovered with HETE[35] was followed by a faint, soft and delayed (∼150 s) X-ray flare, which may point to a different origin. BH–NS mergers in the disk 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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Competing financial interests

The authors declare that they have no competing financial interests.