Mem. S.A.It. Suppl. Vol. 21, 104

Memorie della
Supplementi

Short gamma-ray bursts: evidence for an origin in globular clusters?

R. P. Church[1], A. J. Levan[1,2] M. B. Davies[1] and N. Tanvir[3]

[1] Department of Astronomy and Theoretical Physics, Lund Observatory, Box 43, SE 221 00 Lund, Sweden
[2] Department of Physics, University of Warwick, Coventry. CV4 7AL. UK
[3] Department of Physics and Astronomy, University of Leicester, Leicester. KE1 7RH. UK
e-mail: ross@astro.lu.se

Abstract. We compare the observed spatial offsets of short gamma-ray bursts from their host galaxies with their predicted distributions, assuming that they originate in double neutron star binaries that form from field stars. We find that, for the majority of bursts, this model is sufficient to explain the observed offsets, although there is a trend towards larger offsets than predicted. One burst, GRB 060502B, has an offset that is clearly anomalous. We discuss possible reasons for the large offsets, including host galaxy misidentification, and suggest that some of the largest-offset bursts may originate in the merger of double neutron star binaries that form dynamically in the cores of globular clusters.

Key words. binaries: general – gamma-ray burst: general – neutron stars: general – black holes: general

1. Introduction

The advent of the *Swift* satellite has, for the first time, allowed us to locate the positions on the sky of short-duration gamma-ray bursts (SGRBs) and hence determine their host galaxies. The sample of located short bursts that has built up over the last six years of *Swift* operations covers a range of galaxy types, including elliptical galaxies in which no stars are currently being formed. The bursts are observed to occur with a wide range of spatial offsets from their inferred host galaxies, in some cases occurring well outside the host.

These observations broadly support a picture in which the bursts are powered by the formation of a stellar-mass black hole during the merger of a binary containing either two neutron stars (NS–NS) or a black hole and a neutron star (BH–NS). These mergers are driven by inspiral caused by the emission of gravitational radiation; this leads naturally to a very wide range of merger timescales. Hence SGRBs can occur in non-star-forming hosts. Meanwhile, the kicks expected to be present at the formation of the neutron stars will impart a natal velocity to the binaries, which offers a natural qualitative explanation of the offsets (e.g. Bloom et al. 1999; Fryer et al. 1999).

Utilising the hosts identified by *Swift*, we build on the work of previous authors by considering the bursts on a host-by-host basis. We construct offset distributions based on the

Send offprint requests to: R. P. Church

GRB	$R_{\rm off}$ kpc	$v_{\rm h}$ km/s	$r_{\rm h}$ kpc	$R_{\rm e}$ kpc
050509B	63.7 ± 12.1	664	46.3	21.0
050709	3.55 ± 0.27	110	7.9	1.8
050724	2.54 ± 0.08	532	23.9	4.0
051221A	1.53 ± 0.31	157	15.7	2.2
060502B	73 ± 13	505	20.5	10.5
060801	19.7 ± 14.0	170	18.2	3.0
061006	1.44 ± 0.29	124	9.9	3.7
061201	33.9 ± 0.4	121	9.6	1.8
061210	10.7 ± 6.9	162	16.5	2.6
061217	55 ± 20	141	12.8	1.8
070429B	4.7 ± 4.7	149	14.2	2.1
070714B	3.08 ± 0.47	111	8.9	0.94
070724A	4.76 ± 0.06	435	13.1	3.2
070809	19.61± 1.9	110	8.0	0.92
071227	16.1 ± 0.2	173	18.8	3.1
080905A	18.11± 0.42	170	18.1	3.0

Table 1. Properties of SGRBs in our sample and their host Galaxies. For more details of the population and a complete reference list see (Church et al. 2011).

properties of the observed hosts. We use a sample of 16 bursts, all of which have identified hosts with measured properties including magnitude and redshift. Our burst sample is presented in Table 1.

2. Data and calculations

In order to predict the offsets of short gamma-ray bursts we synthesised a large population of compact binaries using the rapid binary evolution code BSE (Hurley et al. 2002). We retained those binaries that evolved into NS–NS or BH–NS binaries, and computed their final 3D velocities, taking into account the effects of supernova mass loss and natal kicks. We found that, in order to satisfactorily reproduce the orbital properties of Galactic NS–NS binaries, we required strong natal kicks, of the order of $100\,\mathrm{km\,s^{-1}}$. Hence we adopt the Arzoumanian et al. (2002) kick distribution. We present distributions of merger times and rest-frame velocities for our final sample of binaries in Figures 1 and 2.

We model the observed SGRB sample on a burst-by-burst basis. For each host galaxy we produce a separate potential model, utilising the logarithmic potential of Thomas et al. (2009). The core radius $r_{\rm h}$ and halo circular velocity $v_{\rm h}$ for each burst are obtained from the the fits of Kormendy & Freeman (2004) to SDSS data. Fits from the same source were

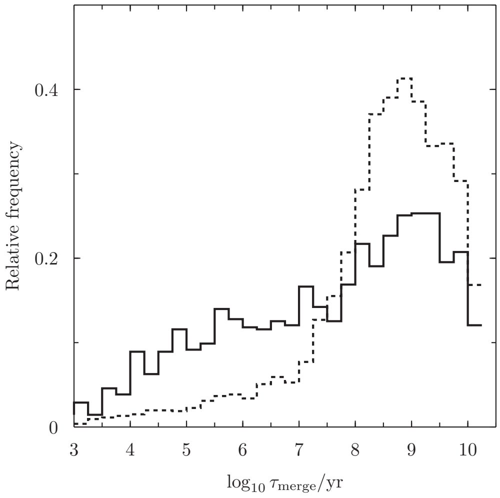

Fig. 1. The merger time distribution of our synthesised binary population. NS–NS binaries are shown in as solid lines; BH–NS binaries as dashed lines.

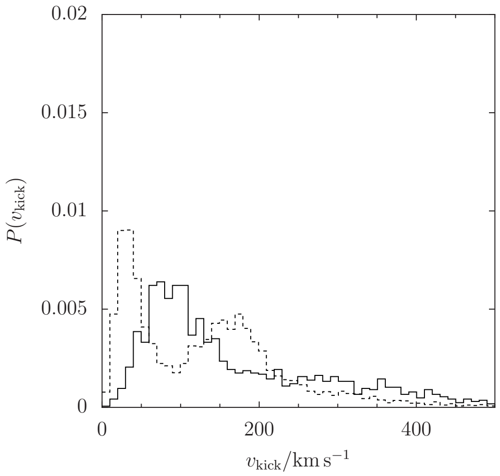

Fig. 2. The velocity distribution of our synthesised binary population after the formation of a double compact binary. NS–NS binaries are shown in as solid lines; BH–NS binaries as dashed lines. Velocities are measured with respect to the initial rest frames of the binaries.

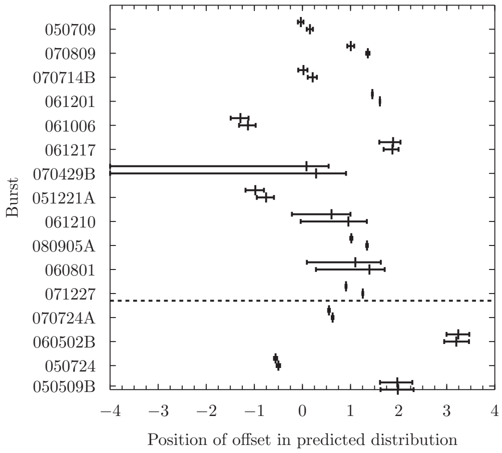

Fig. 3. The observed offset from the host centre for each of the bursts in our sample. To allow the consistent comparison of different hosts we have plotted the difference between the observed offset and the median predicted offset, in units of the standard deviation of its host's predicted offset distribution. For example, a burst which lay at the 98th percentile in the cumulative offset distribution of its host would be plotted at $x = 2$. If the predicted distributions match the observed values then the plot should be symmetric around $x = 0$. For each burst the range plotted is one standard deviation in observed offset. The lower bar in each case is for NS–NS progenitors, the upper for NS–BH progenitors.

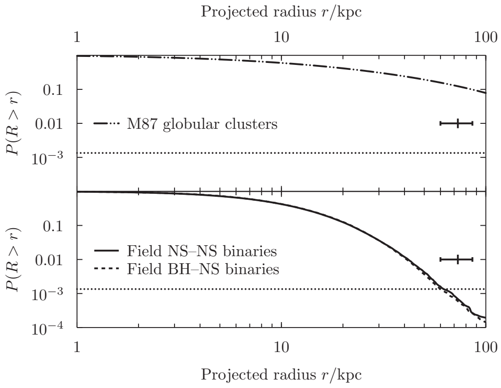

Fig. 4. Lower panel: the cumulative offset probability for bursts around the host of GRB 060502B assuming that the burst comes from a merging field binary. Solid lines show the distributions for bursts from NS–NS binaries; dashed lines show bursts from BH–NS binaries. The error bar, placed at arbitrary height, shows the 1-σ error on the measured offset. The dotted line shows the 3-σ exclusion level. Upper panel: ditto, except for NS–NS binaries that form dynamically in a globular cluster system similar to that around M87.

also used for half-light radii where measured values were not available in the literature. The properties of our haloes are given in Table 1. We form stars in an exponential disc with radial scale length equal to the half-light radius of the host. We place our compact binaries in these discs, endowing them with the calculated velocities in isotropically distributed directions. We integrate the motion of each binary's centre of mass in the potential field of the host for the merger time of the binary, recording the position in the host galaxy where the merger occurs. Finally we project the location onto the host using a random viewing angle. This process is repeated over a large number of realisations to build up an offset distribution for each host.

The position of each observed burst within the offset distribution predicted for its host is plotted in Figure 3. The majority of the bursts are reproduced relatively well by our treatment, although it is evident that the synthesised distributions are systematically underpredicting the host offsets; i.e. the distribution is not centred around $x = 0$. In particular one burst, GRB 060502B, is at an anomalously large offset. The cumulative distribution of predicted offsets for this burst is shown in Figure 4. The possibility of a burst occurring at such a large offset around this host galaxy is excluded at the three-sigma level, although the errors on the burst position are rather large as no optical afterglow was detected.

3. Discussion

There are several possible explanations for the failure of the field binary scenario to reproduce the large offset of GRB 060502B. Firstly, it is possible that the host galaxy has been misidentified. We follow Bloom et al. (2007) in selecting the giant elliptical considered here as the host with a large offset. The probability of a chance co-incidence with this galaxy is only a few per cent; on the other hand there are smaller, fainter galaxies within the XRT error circle (Berger et al. 2007). This is an innate problem in measuring offsets with hosts selected through spatial co-incidence on the sky.

A second possibility is that, for bursts around massive elliptical galaxies, the evolution of the hosts has driven the binaries out to larger offsets. Zemp et al. (2009) compute the distribution of coalescing compact binaries in cosmologically evolving dark matter halos and show that the result is to increase the observed offsets, with the inferred host galaxy not always being the galaxy in which the binary formed. This is a entirely possible origin for the progenitor of GRB 060502B.

The third possibility we consider is that some fraction of bursts originate in compact binaries that have formed dynamically within the globular cluster systems of their host galaxies. Within the cores of globular clusters the number densities are high enough that stars undergo dynamical encounters with one another. Neutron stars, which segregate to the centre of the clusters, can exchange into pre-existing binaries to form NS–NS binaries (Davies 1995). Those binaries then could yield SGRBs. Grindlay et al. (2006) extrapolate from M15-C, the single NS–NS binary that is unambiguously dynamically formed, to derive a merger rate of $R_{\rm gc} = 0.31T(10^9\,M_\odot)^{-1}t^{-1}_{\rm Hubble}$, where T is the number of globular clusters per $10^9\,M_\odot$ of galactic stellar mass. They caution, however, that simple scattering calculations suggest that this rate is an underestimate by a factor of at least ten. Our population synthesis implies a field NS–NS merger rate of $R_{\rm field} = 15 f_{\rm b}(10^9\,M_\odot)^{-1}t^{-1}_{\rm Hubble}$, where $f_{\rm b}$ is the field binary fraction. This suggests that the ratio of rates of field and globular cluster mergers is $\frac{R_{\rm gc}}{R_{\rm field}} \simeq 0.02T/f_{\rm b}$. The nearest elliptical galaxy of similar size to the putative host of GRB 060502B is M87, which has roughly 14 000 globular clusters (Harris 2009) in a very extended distribution. Its specific density of globular clusters is $T \simeq 8$ (Brodie & Strader 2006). Taking into account the underestimate mentioned above and the uncertainty in binary population synthesis calculations this is consistent with a similar rate of burst production in the field and in globular clusters for massive elliptical galaxies. In the upper panel of Figure 4 we plot the cumulative offset distribution given by assuming that GRB 060502B occurred in a globular cluster in a system identical to that of M87. This gives a much better fit to the offset than a field population origin.

Acknowledgements. RPC is funded by a Marie-Curie Intra-European Fellowship, Grant No. 252431 under the European Comission's FP7 framework. This work was supported by the Swedish Research Council (grant 2008–4089). This work utilises computers purchased with the support of the Royal Physiographic Society of Lund.

References

Arzoumanian, Z., Chernoff, D. F., & Cordes, J. M. 2002, ApJ, 568, 289
Berger, E., et al. 2007, ApJ, 664, 1000
Bloom, J. S., et al. 2007, ApJ, 654, 878
Bloom, J. S., Sigurdsson, S., & Pols, O. R. 1999, MNRAS, 305, 763
Brodie, J. P. & Strader, J. 2006, ARA&A, 44, 193
Church, R. P., Levan, A. J., Davies, M. B., & Tanvir, N. 2011, MNRAS, 413, 2004
Davies, M. B. 1995, MNRAS, 276, 887
Fryer, C. L., Woosley, S. E., & Hartmann, D. H. 1999, ApJ, 526, 152
Grindlay, J., Portegies Zwart, S., & McMillan, S. 2006, Nature Physics, 2, 116
Harris, W. E. 2009, ApJ, 703, 939
Hurley, J. R., Tout, C. A., & Pols, O. R. 2002, MNRAS, 329, 897
Kormendy, J. & Freeman, K. C. 2004, in IAU Symposium, Vol. 220, Dark Matter in Galaxies, ed. S. Ryder, D. Pisano, M. Walker, & K. Freeman, 377–+
Thomas, J., et al. 2009, ApJ, 691, 770
Zemp, M., Ramirez-Ruiz, E., & Diemand, J. 2009, ApJ, 705, L186