Occurrence of potentially hazardous GRBs launched in globular clusters

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ABSTRACT

Context. Nearby, Galactic gamma-ray bursts (GRBs) may affect the terrestrial biota if their radiation is beamed towards the Earth. Compact stellar binary mergers are possible central engines of short GRBs and their rate could be boosted in globular clusters.

Aims. The occurrence, impact on the terrestrial biota and the point in time of the explosion of the closest GRB launched in a globular cluster are explored.

Methods. Globular cluster typically follow well defined orbits around the galactic center. Therefore their position relative to the solar system can be calculated back in time. This fact is used to demonstrate that globular cluster - solar system encounters define possible points in time when a nearby GRB could have exploded. Additionally, potential terrestrial signatures in the geological record connected to such an event are discussed.

Results. Assuming rates of GRBs launched in globular cluster found from the redshift distribution of short burst and adopting the current globular cluster space-density around the solar system it is found that the expected minimal distance \(d_{\text{min}}\) for such a GRB in the last 600 Myrs is about 2 kpc. From the average gamma-ray luminosity of a short GRB significant depletion of the terrestrial ozone-layer is expected if such an event explodes at a distance of \(d_{\text{min}} \approx 1 - 3.5\) kpc. From the recent measurements of the gamma-ray luminosity of GRB 100316A significant depletion of the terrestrial ozone-layer is expected if such an event explodes at a distance of \(d_{\text{min}} \approx 1 - 3.5\) kpc. In the last 500 Myrs a few globular cluster passages are expected within a distance of \(d_{\text{min}}\) for a GRB that should have exploded during one of these passages.

Conclusions. Globular cluster - solar system encounters and events of mass extinction in the history of life can be correlated to investigate the impact of a nearby GRB on the terrestrial biota. To explore such a correlation reliable globular cluster positions relative to the solar system have to be calculated for the time span of the fossil record of the last 600 Myrs. The upcoming GAIA mission will be crucial to determine the possible time intervals of the occurrence of nearby GRBs launched in globular clusters.

Key words. globular clusters: general – Gamma-ray burst: general – Proper motions – Astrobiology

1. Introduction

Gamma-ray bursts (GRBs) are powerful cosmological explosions which irradiate their surroundings in two cones with high energy photons (see Gehrels et al., 2009, for a review). It has been recognized that due to this radiation, galactic GRBs can have a dramatic effect on the earth atmosphere and on the biota (Thorsett, 1995). Furthermore, it has been pointed out that besides the extinction of species cosmic rays connected to GRBs can cause biological mutations leading to fast appearance of new species after these mass extinction events (Dar et al., 1998). Indeed the evolution of life on earth was affected by several events of mass-extinction (Raup & Sepkoski, 1982) and show also periods of rapid development of new species (e.g. Cambrian explosion (Marshall, 2006). From the observed rate of GRBs it is evident that a nearby (\(d \sim 1\) kpc) burst is likely during the geological record and such an event has been linked to the late Ordovician mass extinction event that happened 440 Myr in the past (Melott et al., 2004). Additionally, Horvath (2003) has suggested that the Cambrian explosion 543 Myr ago could have been triggered by a nearby GRB. In general, the exact point in time when a nearby GRB has happened is difficult to identify. This challenges the correlation between a certain event in the history of the Earth and the occurrence of a nearby GRB.

GRBs appear to be launched by two distinct populations of progenitors. Long bursts (duration \(\gtrsim 2\) s) appear to be connected to the death of massive stars whereas short burst (duration \(< 2\) s) seem to result from the merger of two compact objects (see Gehrels et al., 2009, for a review).

For short bursts it has been shown that their rate can be boosted in globular clusters due to the efficient production of close stellar binaries in their cores (Grindlay et al., 2006; Lee et al., 2010). Several observational facts support the association between short GRBs and globular clusters. Firstly, in the globular cluster M 15 a close binary consisting of two neutron stars has already been discovered (Anderson et al., 1999). Secondly, from the off-set distribution of short bursts from their host galaxies it has been inferred that a subset of bursts can originate in globular clusters (Berger, 2010; Salvaterra et al., 2010; Church et al., 2011). Thirdly, from the redshift distribution of short burst it has been concluded that in the local universe the short GRB rate is dominated by dynamically formed compact binaries in globular clusters (Salvaterra et al., 2008; Guetta & Stella, 2009). Finally, the occurrence of short GRBs in globular clusters is consistent with the recent redshift distribution of short burst (Berger et al., 2011). The recent GRB 100316A (Clapson et al., 2011) is a candidate for a GRB launched in a globular cluster (Domainko & Rueter, 2011).
to be evidence that a considerable rate of GRBs are launched in globular clusters.

Globular clusters typically follow well defined orbits around the center of the Milky Way. Proper motions are available for a number of globular clusters (Dinescu et al., 1997, 1999a,b) and this allows to determine their orbital motions (Allen et al., 2006). Thus, their position relative to the Earth can be traced back in time (Vande Putte & Cropper, 2009). Encounters of globular clusters and the Earth are potential time intervals during which to the biota hazardous, nearby bursts can occur. Consequently it is possible to identify such periods by tracing back the distance of globular cluster to the Earth.

The observed values for the proper motion of globular clusters are still affected by considerable errors. Vande Putte & Cropper (2009) found that the relative position between the Earth and various globular clusters can be traced back in time reliably only for about 50 Myr. Since this time span is considerably shorter than the geological record, in this paper the possibility of a correlation between globular cluster passages and events in the history of the Earth are investigated on a statistical basis.

This paper is organized as follows: firstly the expected minimum distance to a GRB launched in a globular cluster will be determined. Secondly, potential terrestrial signatures connected to a GRB happening at this minimal distance are investigated. Thirdly, it will be shown that with determining the time intervals of globular cluster - solar system encounters points in time can be identified, where in principal nearby GRBs can happen. And finally the prospects for correlating such globular cluster passages and events of mass extinction are discussed.

2. Minimal distance

To determine the expected minimum distance to Earth of a GRB launched in a globular cluster in the last Gyr, first the rate of such events per globular cluster has to be constrained. The estimated rate of GRBs originating in globular clusters that are beamed towards the Earth ranges from \( R_{GC} \sim 4 \text{ Gpc}^{-3} \text{yr}^{-1} \) (Guetta & Stella, 2009) to \( R_{GC} \sim 20 - 90 \text{ Gpc}^{-3} \text{yr}^{-1} \) (Salvaterra et al., 2008). Using now the density of globular clusters in the local universe of about 3 Mpc\(^{-3} \) (Portigies Zwart & McMillan, 2000) this results in a GRB rate of \( \phi \approx 10^{-3} (R_{GC}/30 \text{ Gpc}^{-3} \text{yr}^{-1}) \) per year per globular cluster. From this estimate the expected minimum distance \( d_{\text{min}} \) for a GRB exploding in the last Gyr can be estimated. For an event rate of \( 10^{-3} \) per year \( d_{\text{min}} \) is given by the volume around the Earth where the probability to find a globular cluster is \( 10^{-3}/\Phi \approx 0.1 \times (R_{GC}/30 \text{ Gpc}^{-3} \text{yr}^{-1})^{-1} \). The resulting minimal distance is then given by:

\[
d_{\text{min}} \approx \left[ \frac{3}{4\pi} \left( \frac{0.1 \times R_{GC}}{30 \text{ Gpc}^{-3} \text{yr}^{-1}} \right)^{-1} \left( \frac{\rho_{GC}}{\text{kpc}^{-3}} \right)^{-1} \right]^{1/3} \text{kpc}
\]

Here \( \rho_{GC} \) is the number density of globular clusters around the Earth. Adopting a local number density of globular clusters of 0.006 kpc\(^{-3} \) (Djorgovski & Meylan, 1994) this results in a minimum distance of about 1.6 kpc for a short GRB rate launched in globular clusters of \( R_{GC} = 30 \text{ Gpc}^{-3} \text{yr}^{-1} \). The dependence of \( d_{\text{min}} \) on the parameters \( R_{GC} \) and \( \rho_{GC} \) is shown in Fig. 1. For reasonable input parameters \( d_{\text{min}} \) falls between \( 1 - 3.5 \text{kpc} \).

1 assuming \( h = 0.7 \)

3. Terrestrial signatures

Potential terrestrial signatures generated by a nearby GRB could comprise the impact on the biota in-printed in the fossil record (see Galante & Horvath, 2007, for a discussion on various to the biota hazardous effects connected to a nearby burst), a glaciation event following reduced atmospheric transparency due to NO\(_2\) production by the ionizing radiation of a GRB (Thomas et al., 2005), anomalies of radioactive isotopes or fossil cosmic ray tracks (Dar et al., 1998). From the expected minimal distance of a GRB launched in a globular cluster the strength of corresponding terrestrial signatures can be estimated.

3.1. Impact on the biota

Depletion of the ozone-layer has been found to be an important consequence of a nearby GRB explosion for the biota (Thorsett, 1995; Thomas et al., 2005). The level of depletion of the ozone-layer will depend on the fluence of X-rays and soft gamma-rays from the GRB. If the mean isotropic gamma-ray luminosity \( E_{\gamma,\text{iso}} = 6.5 \times 10^{50} \text{ erg} \) found for short bursts by Swift-BAT (Racusin et al., 2011) is adopted this results in a fluence of \( 6 \times 10^{50} \text{ erg cm}\(^{-2} \) at a distance of 1 kpc. In comparison to that value, Galante & Horvath (2007) estimated the critical fluence of a GRB to destroy the ozone layer on a level where damages on the biota will occur to \( 3 \times 10^{50} \text{ erg cm}\(^{-2} \) and also Thomas et al. (2005) found significant ozone depletion for the case of \( 10^{50} \text{ erg cm}\(^{-2} \). Consequently its possible that a short GRB at a distance of up to 1.5 kpc will have an effect on the biota. To conclude, for advantageous estimates for the GRB rate in globular clusters it appears possible that the closest such event has left terrestrial signatures in form of an extinction event that is in-printed in the fossil record.

3.2. Radioactive nuclei

One example for potentially measurable signatures are radioactive nuclei produced by either the enhanced cosmic ray flux (Dar et al., 1998) or by high energy gamma-ray photons (Thorsett, 1995) connected to the GRB.
Ultra-relativistic shock waves are expected to convert most of their kinetic energy into cosmic rays (Atovan et al., 2006). Following this argument by assuming that the mean kinetic energy estimated for short bursts with Swift-BAT of $2.5 \times 10^{52}$ erg (Racusin et al., 2011) is converted into cosmic rays and that the cosmic ray jet is still collimated at a distance of 1 kpc this will result in a cosmic ray fluence of $2 \times 10^{46}$ erg cm$^{-2}$ at this distance. This corresponds to the integrated energy deposition of galactic cosmic rays for about 100 years. Thus cosmic rays produced by the GRB can in principle create an anomaly of radioactive nuclei. However, since terrestrial rocks are typically exposed to cosmic rays much longer than 100 years its quite unlikely that cosmic rays connected to a GRB will leave measurable traces in form of radioactive isotopes in the geological record.

Some short GRBs show gamma-ray emission with photon energies above 100 MeV (Abdo et al., 2009) but it has to be noted that only few GRBs are detected in this energy band (e.g. Zhang et al., 2011). For the case of GRB090510 the high energy component had an isotropic luminosity of about $4 \times 10^{52}$ erg (Abdo et al., 2009). This high-energy luminosity can result in a comparable fluence of high-energy gamma-ray photons as has been estimated for the cosmic ray fluence in the previous paragraph. Consequently, also the energy deposition of high energy gamma-ray photons can equal the galactic cosmic ray energy deposition integrated over about 100 years if such a burst is located at a distance of 1 kpc. However, again quite unlikely that high-energy photons will leave measurable traces in the geological record in form of radioactive nuclei.

To conclude, even for advantageous estimates for the GRB rate in globular cluster it quite unlikely that these GRBs have left anomalies of radioactive isotopes in the geological record. However, for a short period of time ($\lesssim$ 100 years) they could have elevated the level of radioactivity which could cause biological mutations leading to fast appearance of new species.

4. Association with terrestrial signatures

Nearby GRBs launched in globular clusters offer the exciting possibility to calculate back the approximate time of their occurrence. This can be done due to the fact that globular clusters follow quite well defined orbits around the galactic center (Allen et al., 2006) and therefore the time of encounters between the solar system and a specific globular cluster can be determined (see e.g. Vande Putte & Cropper, 2009). Here a globular cluster encounter is defined as a time period when the distance between the solar system and the globular cluster is smaller than $d_{\text{min}}$.

With the knowledge of the fraction of time where at least one globular cluster can be found within $d_{\text{min}}$ (see Sec. 2) and with adopting the duration of a typical globular cluster – Earth encounter the number of such encounters can be estimated for a specific time interval. In Sec. 2 it was estimated that during a fraction of about 0.1 ($\frac{R_{\text{GC}}}{30 \text{ Gpc}}$)$^{-1}$ yr of the time considered, one globular cluster is found within the minimal distance $d_{\text{min}}$ for a GRB occurrence. A typical encounter will last for $O(10^7)$ years of if an encounter length of $\sim$ 1 kpc and a relative velocity between the earth and the globular cluster of $\sim$ 100 km s$^{-1}$ is assumed. If now a GRB rate $\dot{R}_{\text{GC}} = 30 \text{ Gpc}^{-3}\text{yr}^{-1}$ is considered this results in a total period of $10^8$ years of presence of at least one globular cluster within $d_{\text{min}}$ in the last Gyr. With a typical encounter duration of $\sim 10^7$ years $O(10)$ globular cluster – Earth encounters within a distance of $d_{\text{min}}$ are expected.

The expected probability for a GRB occurring in a globular cluster during an encounter can be estimated from the rate of GRBs per globular cluster and the duration of an globular cluster – Earth encounter. If for this rate a value of $\Phi \approx 10^{-8}$ $(R_{\text{GC}}/30 \text{ Gpc}^{-3}\text{yr}^{-1})$ per globular cluster per year (see Sec. 2) is adopted and a typical duration of a globular cluster passage of $10^7$ years is assumed, then the resulting probability is $\Phi \times 10^7$ years $\approx 0.1 (R_{\text{GC}}/30 \text{ Gpc}^{-3}\text{yr}^{-1})$. For a GRB rate of $\dot{R}_{\text{GC}} = 30 \text{ Gpc}^{-3}\text{yr}^{-1}$ on average one GRB is expected every 10 globular clusters – Earth encounters. Thus for the time span of the geological record one GRB is likely during a globular cluster-solar system encounter.

In the above considerations it is assumed that the GRB rate is the same for each globular cluster. However, some globular clusters are especially prolific producers of close binaries (Poole & Hut, 2006). These objects likely exhibit also a higher GRB rate (Grindlay et al., 2006; Lee et al., 2010). Consequently, the passage of a globular cluster hosting a large number of stellar binaries close to Earth can be identified as a potential time interval of a nearby GRB explosion.

As a result of the above considerations, specific time intervals corresponding to globular cluster encounters can be identified for which the geological record can be searched for potential terrestrial signatures connected to a nearby GRB. Furthermore correlations between events of mass extinction in the history of life (Raup & Sepkoski, 1982) or periods of rapid development of new species (e.g. Cambrian explosion Marshall, 2006) with periods of globular cluster encounters can be explored. With a few globular cluster passages during the last 600 Myr and a typical duration of $O(10^7)$ years for each passage a fair fraction of chance coincidence between events of mass extinctions and globular cluster passages can be expected. Considering only passages of globular clusters hosting an elevated number of close binaries can help to reduce the probability of such a chance coincidence.

5. Outlook

In Sec. 4 it has been pointed out that periods with globular cluster passages close to the solar systems can be determined. During these time periods nearby GRB events launched in globular clusters could have happened. For determining the impact of nearby GRBs on the biota by correlating globular cluster passages and events of mass extinction, it is necessary to reliably calculate the globular cluster distance for the last 600 Myrs. An accurate determination of globular cluster positions appear in principle possible since the time span of 600 Myrs corresponds to only a few globular cluster orbits around the galactic center that last typically $O(100)$ Myrs.

Assuming a velocity of the globular clusters of $O(100)$ km s$^{-1}$ an accuracy of about 1% for the 3d motion would be needed to constrain their position to $\sim$ 1 kpc for the last Gyr. However, with the current precision reliable calculations of the cluster position with respect to the Earth can only be calculated back for about 50 Myrs ago (see Vande Putte & Cropper, 2009).

The required accuracy for the 3d motion of galactic globular clusters will likely be available in the foreseen future. The upcoming GAIA mission[2] will provide unprecedented positional and radial velocity measurement of about one billion stars in the Milky Way. With these data it will be possible to calculate accurate globular cluster orbits and to identify periods of encounters with the solar system. Encounters between globular clusters with an exceptionally elevated number of close binaries

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2 http://gaia.esa.int/
(Pooley & Hut, 2006) can be identified as potential point in time for a nearby GRB explosion. These points in time can be compared to events of mass extinction and for the case that there is no correlation with such events, the geological record can be searched for any terrestrial signatures connected to a nearby GRB explosion.

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