

A Galactic short gamma-ray burst as cause for the ^{14}C peak in AD 774/5

V. V. Hambaryan^{*} and R. Neuhäuser

Astrophysikalisches Institut, Universität Jena, Schillergässchen 2-3, D-07745 Jena, Germany

Accepted 2012 November 7. Received 2012 November 2; in original form 2012 September 7

ABSTRACT

In the last 3000 yr, one significant and rapid increase in the concentration of ^{14}C in tree rings was observed; it corresponds to a γ -ray energy input of 7×10^{24} erg at Earth within up to one year in AD 774/5. A normal supernova and a solar or stellar flare are unlikely as cause, so that the source remained unknown. Here, we show that a short gamma-ray burst (GRB) in our Galaxy is consistent with all observables: such an event is sufficiently short and provides the necessary energy in the relevant spectral range of γ -rays. Its spectral hardness is consistent with the differential production rates of ^{14}C and ^{10}Be as observed. The absence of reports about a historic sighting of a supernova in AD 774/5 or a present-day supernova remnant is also consistent with a short GRB. We estimate the distance towards this short GRB to be $\sim 1\text{--}4$ kpc – sufficiently far away, so that no extinction event on Earth was triggered. This is the first evidence for a short GRB in our Galaxy.

Key words: gamma-ray burst: general – stars: neutron – supernovae: general – white dwarfs.

1 INTRODUCTION: THE AD 774/5 EVENT

A significant increase in the ^{14}C to ^{12}C isotope ratio was detected in Japanese trees in AD 774/5 and a subsequent decrease for ~ 10 yr (Miyake et al. 2012, hereafter M12). It is consistent with an increase in ^{14}C in American and European trees with 5–10 yr time resolution (Stuiver et al. 1998). If deposited within one year or less – best consistent with an atmospheric deposition model – the increase is 10 times larger than the average production due to Galactic cosmic rays and 20 times larger than expected from the 2×11 yr solar cycle (M12). This requires a γ -ray energy input of 7×10^{24} erg at Earth (M12). Moreover, a 30 per cent increase in ^{10}Be around AD 775 was observed in Antarctica, but with lower time resolution (Horiuchi et al. 2008). Solar or stellar flare was found to be unlikely because of the insufficient energetics and spectrum of such flares (M12). A normal supernova (SN) was also found to be unlikely from the lack of any historical sighting or a supernova remnant (SNR; M12).

2 SUPERNOVA OR MAGNETAR FLARE?

A strongly absorbed SN was not considered quantitatively, yet. Absorption in the line of sight would not affect γ -rays, but would decrease the observable optical flux of an SN. Of the total energy output of an SN, $E(\text{event}) = 10^{51}$ erg, a fraction $g = 0.01$ goes into γ -rays (Richardson et al. 2002). The ratio between the γ -ray energy emitted by an SN event spread homogeneously into the total area of a spherical shell around the SN ($4\pi d^2$ with distance d from the

event to Earth) and the γ -ray energy $E(\text{obs})$ observed at Earth is equal to the ratio between the surface area of that sphere and the Earth solid angle πR^2 (with Earth radius R):

$$\frac{E(\text{event}) \times g}{E(\text{obs})} = \frac{4\pi d^2}{\pi R^2}. \quad (1)$$

Therefore, a normal SN (with $g = 0.01$), of which a γ -ray flux of $E(\text{obs}) = 7 \times 10^{24}$ erg was observed at Earth, would have a distance $d \simeq 124$ pc, independent of absorption. If the AD 774/5 event were one of the rare (1 per cent) overluminous SNe, up to four times brighter than normal SNe (Richardson et al. 2002), then the expected distance is $d \simeq 260$ pc. From the peak absolute magnitude M (Richardson et al. 2002), we can estimate the unabsorbed apparent peak magnitude:

$$\begin{aligned} m &= -14.0 \pm 0.5 \text{ mag, } 124 \text{ pc, } M = -19.5 \pm 0.5 \text{ mag, SN Ia,} \\ m &= -12.5 \pm 1.0 \text{ mag, } 124 \text{ pc, } M = -18.0 \pm 1.0 \text{ mag, SN II,} \\ m &= -13.2 \pm 0.3 \text{ mag, } 260 \text{ pc, } M = -20.3 \pm 0.3 \text{ mag, SN Ibc.} \end{aligned}$$

One would need absorption of at least $A_V \simeq 13$ mag to disable a historical sighting by naked eye (limit $m \simeq 2$ mag for discovery of a new object; Strom 1994). Such a strong absorption within ~ 124 or 260 pc is not possible, except in small areas towards dark clouds (Reipurth 2008): the closest dark clouds with $A_V \geq 13$ mag are Lynds 183 at ~ 110 pc with up to $A_V = 150$ mag (Pagani et al. 2004) and ρ Oph at ~ 119 pc with up to $A_V = 65$ mag (Lombardi, Lada & Alves 2008; Sadavoy et al. 2010). Absorption of $A_V \geq 13$ mag is limited to 56 deg^2 on the sky (Dobashi 2011; K. Dobashi, private communication) and less for distances within 124–260 pc (Reipurth 2008). The probability of an event within 56 deg^2 of the whole sky is 0.0013. Even then, a large, young and bright SNR

^{*}E-mail: vvh@astro.uni-jena.de

would be detectable by X-ray pointings, but can be excluded (Green 2009; Chandra SNR catalogue¹).

Given the measurement precision achieved in ^{14}C for the 7.2σ peak in AD 774/5 (M12), potential ^{14}C from SNe can be detected up to ~ 200 pc with 3σ . Indeed, there are no SNe, pulsars or SNR known within a few hundred pc with age of some 300–2000 yr (Strom 1994; Manchester et al. 2005, footnote 1; Green 2009; McGill SGR/AXP catalogue²). There are 11 events with evidence (historic observation, detected SNR and/or known pulsar) for an SN within 2000 yr and 5 kpc (Strom 1994; Manchester et al. 2005, footnotes 1 and 2; Green 2009) and for all of them, an SNR is detected (Green 2009), and at least eight were observed historically (Strom 1994). While a missing historic observation is possible, a missing SNR is very unlikely.

Magnetar flares (soft gamma-ray repeaters or anomalous X-ray pulsars) were not yet considered: the largest flare observed was the X- and γ -ray flare of SGR 1806–20 on 2004 December 27 with peak energy $(3.7 \pm 0.9) \times 10^{46}$ erg s^{-1} at 15 kpc (Hurley et al. 2005) or $E(\text{event}) = 2 \times 10^{46}$ erg at 8.7 ± 1.7 kpc (Bibby et al. 2008). If the AD 774/5 event were such a flare, it would have taken place at ~ 5.5 pc (equation 1 with $g = 1$), but there is no neutron star known within such a small distance (Manchester et al. 2005, footnote 2). Even if a magnetar with 10^{16} G dipole field could produce an event with 10^{48} erg (Hurley et al. 2005), the distance of such a neutron star to produce the AD 774/5 event would have to be ~ 39 pc. A magnetar at that small distance would have been detected by the *ROSAT* all-sky X-ray survey: for a persistent bolometric luminosity (mostly X-rays) of $\sim (0.025\text{--}1.6) \times 10^{35}$ erg s^{-1} with typical observed spectral components of magnetars (blackbody with peak energy $kT = 0.4$ keV and power-law index ~ 3 , footnote 2), we expect $150\text{--}800\,000$ counts s^{-1} in the *ROSAT* energy band 0.1–2.4 keV at 10 to even 100 pc, i.e. easily detectable. Hence, we can exclude magnetar flares for the AD 774/5 event.

3 A SHORT GAMMA-RAY BURST

Given that events on Earth as well as solar and stellar flares (M12) including neutron star flares (see above) as well as unabsorbed (M12) and absorbed SNe are very unlikely to be the cause for the AD 774/5 cosmic ray event (see above), we will now consider a gamma-ray burst (GRB). The observed duration and spectral hardness of GRBs allow us to divide them into long (≥ 2 s) and short (≤ 2 s) GRBs; the latter are harder regarding the spectrum (power law with exponential cut-off) and are not related to SNe or SNRs (Nakar 2007). While long GRBs are caused by the core collapse of a very massive star, short GRBs are explained by the merger of two compact objects (Nakar 2007). A merger of two previously orbiting compact objects is the coalescence of a neutron star with either a black hole becoming a more massive black hole, or with another neutron star becoming either a relatively massive stable neutron star or otherwise a black hole, if the total mass exceeds the upper mass limit of neutron stars, somewhere between 2 and $3 M_{\odot}$. For example, the merger of two magnetized neutron stars can produce a spinning black hole launching a relativistic jet as observed in short GRBs (Rezzolla et al. 2011), if the Earth is located in the jet. Let us now consider a short GRB.

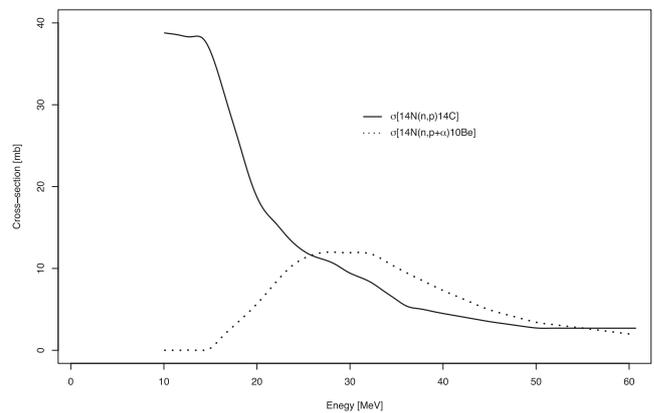


Figure 1. Energy dependence of the relevant cross-sections for producing ^{14}C and ^{10}Be . We plot the energy dependence of the cross-sections σ of the reactions $^{14}\text{N}(n,p)^{14}\text{C}$ and $^{14}\text{N}(n,p+\alpha)^{10}\text{Be}$ as solid and dotted lines, respectively, cross-section in milli-barn (mb, 1 barn is 10^{-28} m²) versus energy in MeV.

3.1 Energetics, time-scale and spectrum

A short GRB emits an isotropic equivalent energy of $E(\text{event}) = 10^{49}\text{--}10^{52}$ erg in the observed energy range 10 keV to 30 GeV (Berger 2007; Nakar 2007), most or all in γ -rays ($g = 0.1\text{--}1$). We estimate the distance towards a short GRB from equation (1) to $d \simeq 0.1\text{--}3.9$ kpc, i.e. within our Galaxy. Hence, the energetics of the ^{14}C peak on Earth are consistent with a short GRB.

Effects of nearby long GRBs on the Earth biosphere due to the direct hit (5×10^{51} erg s^{-1} for 10 s) on one half-sphere were found to be lethal within ~ 2 kpc (Melott et al. 2004; Thomas et al. 2005). This can be scaled to a short GRB with $10^{49}\text{--}10^{52}$ erg. Hence, for a short GRB within ~ 1 kpc, strong extinction effects are expected. Because no extinction event was observed on Earth for AD 774/5, the short GRB was more distant, probably $\sim 1\text{--}4$ kpc.

A transient event is expected in the optical (macronova) from compact mergers with $M_V = -15$ mag at peak (Metzger & Berger 2012; Piran, Nakar & Rosswog 2012). This corresponds to $m_V = -10$ (0.1 kpc) or $m_V = -2$ mag (4 kpc) for negligible absorption. Hence, it may have been observable by naked eye, but only for up to one day, i.e. much shorter than a typical SN. If reports about such a sighting remain missing, it can be due to the short time-scale, strong absorption, bad weather and/or sky location near the Sun and/or above unpopulated areas such as the Pacific during the short visibility period. A missing historical observation and a missing SNR are fully consistent with a short GRB.

Since the peak of ^{14}C observed in AD 774/5 is consistent with a sharp increase within 0.1–1 yr (M12), a short GRB typically lasting less than 2 s (Nakar 2007; Rezzolla et al. 2011) and being undispersed in interstellar space is consistent with the observations regarding the short time-scale.

Given the cross-sections³ of the relevant reactions producing ^{14}C and ^{10}Be (Fig. 1) and the full range of observed spectral parameters of short (Nakar 2007; Ghirlanda et al. 2009) and long (Band function; Band et al. 1993) GRBs (Fig. 2), we computed the outcome (Fig. 3). We assume that the peaks in ^{14}C (19 ± 4 atoms cm^{-2} s^{-1} in ≤ 1 yr; M12) and ^{10}Be (30 per cent increase with 10 yr time resolution; Horiuchi et al. 2008) were both due to the same event, i.e. produced within one year. Then, with the known background

¹ http://hea-www.harvard.edu/ChandraSNR/snrcat_gal.html

² <http://www.physics.mcgill.ca/pulsar/magnetar/main.html>

³ <http://www-nds.iaea.org> (Dimbylow 1980; Burger & Ebert 1981).

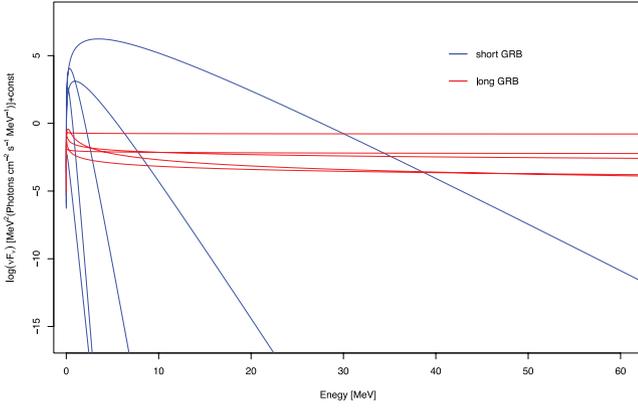


Figure 2. Typical spectra of short and long GRBs. We plot the flux νF_ν (with frequency ν) versus energy in MeV sampling the whole range of parameters observed, i.e. several typical spectra as blue and red lines for short and long GRBs, respectively. We plot the flux as log of νF_ν in $\text{MeV}^2 \text{ photons cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$ (plus arbitrary scaling due to normalization). At the observable low γ -ray energies, we see that short GRBs are harder than long GRBs, hence the division and naming. We use equations (2) and (3) and the Band function (Band et al. 1993) to estimate the production rate of ^{14}C to ^{10}Be from the input spectra for short and long GRBs. Because long GRBs have a flat spectrum (Band function), they cannot reproduce the observed production rate of ^{14}C to ^{10}Be ($\geq 270 \pm 140$), while short GRBs can reproduce the observed ratio, see Fig. 3.

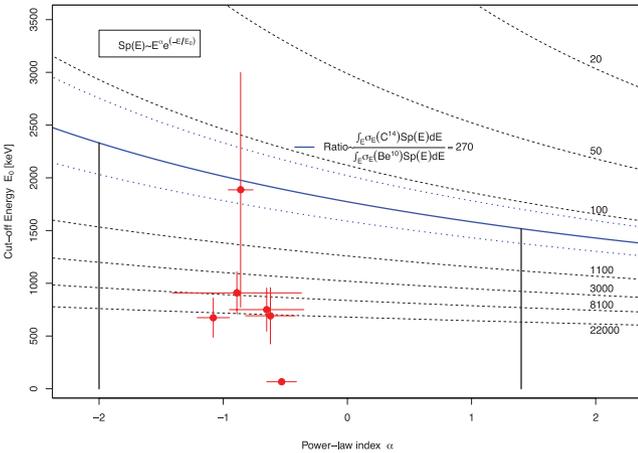


Figure 3. The typical spectrum of short GRBs can explain the differential production rates of ^{14}C to ^{10}Be observed to be at least 270 ± 140 . Given the typical energy spectrum of a short GRB with a power-law index $\alpha = -2$ – -1.4 (vertical black lines) and a cut-off energy $E_0 = 49$ – 1900 keV (Nakar 2007; Ghirlanda et al. 2009), and also given the cross-sections of the reactions $^{14}\text{N}(n,p)^{14}\text{C}$ and $^{14}\text{N}(n,p+\alpha)^{10}\text{Be}$ from 10 to 60 MeV (footnote 3), we estimated the expected fraction for a grid of α and E_0 . The observed lower limit on this fraction (270 ± 140 , 1σ error) is shown as blue curve with dotted lines as error margin. The dashed black lines indicate the ratio of ^{14}C to ^{10}Be production from low values in the upper right to high values in the lower left. We also show the observed power-law indices and cut-off energies of all six short GRBs with known redshifts (Ghirlanda et al. 2009) as red dots with vertical and horizontal red 1σ error bars. Because the power-law index and the cut-off energy needed to reproduce the observed lower limit of 270 ± 140 lie in the typical range of short GRBs and because all data points of local short GRBs lie on or below the line for 270 ± 140 , the observed production rate of ^{14}C to ^{10}Be in AD 774/5 is well consistent with a typical short GRB.

rates for ^{14}C (M12) and ^{10}Be (Horiuchi et al. 2008), we conclude that 270 ± 140 (1σ error) times more ^{14}C was produced than ^{10}Be , above the respective backgrounds. Since some of the ^{10}Be production may have been produced by some other effects in that decade (lower time resolution), this ratio can be considered as a lower limit. We can compare this to the expected outcome for a short GRB. The typical energy spectrum of a short GRB is

$$\text{Sp}(E) \sim E^\alpha \times e^{-E/E_0}, \quad (2)$$

with a power-law index α and a cut-off energy E_0 (Nakar 2007; Ghirlanda et al. 2009). We obtained the cross-sections σ for the reactions $^{14}\text{N}(n,p)^{14}\text{C}$ and $^{14}\text{N}(n,p+\alpha)^{10}\text{Be}$ from $E = 10$ to 60 MeV (footnote 3). We show the dependence of the cross-sections σ on the energy E for both reactions in Fig. 1. Then, we integrated the cross-section σ at that energy range E multiplied by the typical short GRB spectra $\text{Sp}(E)$ over the energy E from 10 to 60 MeV for both ^{14}C and ^{10}Be to obtain the expected ratio

$$\frac{\int_E \sigma(^{14}\text{C}) \times \text{Sp}(E) dE}{\int_E \sigma(^{10}\text{Be}) \times \text{Sp}(E) dE}. \quad (3)$$

Given the definition of cross-section, both the numerator and the denominator in this equation are proportional to the respective number of atoms produced.

We estimated the ratio as expected differential production rates for a grid of α and E_0 as observed for short GRBs, i.e. power-law index α from -2 to 1.4 and cut-off energy E_0 from 49 to 1900 keV (Nakar 2007; Ghirlanda et al. 2009), using XSPEC. The results are shown in Fig. 3. We then also estimated the expected fraction of ^{14}C to ^{10}Be production over the backgrounds for a long GRB with a Band function as spectrum (Band et al. 1993), i.e. a smoothly broken power law. Again, we used the full range of parameters observed for all those long GRBs, where all three spectral parameters were obtained by good fits, namely for the first index α from -1.40 to 0.07 , for the second index β from -3.68 to -2.04 and for the cut-off energy E_0 from 52 to 2867 keV (not redshifted) for long GRBs observed by *Fermi* or BATSE (Nakar 2007; Ghirlanda et al. 2009; Zhang et al. 2011).

Fig. 2 shows qualitatively that a long GRB with a model of a smoothly broken power law (Band function) cannot explain that the ^{14}C production was so much larger than the ^{10}Be production given the energy dependence of the cross-sections of those reactions. Our detailed calculations show that a long GRB with the Band function would produce only up to 18 times more ^{14}C than ^{10}Be . Only a short GRB can explain this observable (ratio $\geq 270 \pm 140$).

3.2 Rates of gamma-ray bursts and mergers

The rate of ^{14}C peaks (one in 3000 yr) is not well constrained, but non-zero; the error of the rate is fully unconstrained.

The rate of short GRBs is $8_{-3}^{+5} \text{ Gpc}^{-3} \text{ yr}^{-1}$ (Coward et al. 2012), all observed and pointed at us. Using then $\sim 0.003 \text{ Mpc}^{-3}$ as the number density of typical galaxies (Melott et al. 2004), we have one short Galactic GRB in 375_{-144}^{+225} kyr beamed towards Earth. If we restrict this estimate to the Galactic disc within 4 kpc, the observed rate is 10 times lower, i.e. one nearby Galactic GRB beamed at us in 3750_{-1442}^{+2250} kyr. Given the sensitivity limits of detectors like BATSE and SWIFT, this is a highly uncertain lower limit. While this is not consistent with one event in 3000 yr within 1σ , it is consistent within 2.6σ . Given that the error of the ^{14}C event rate is unknown, it is consistent with the rate of local short GRBs even within $\leq 2.6\sigma$.

Even though the possible connection between short GRBs and compact mergers are not of central importance for our arguments,

because we use only real observables of short GRBs, we will now consider the rates of mergers of compact objects. From the three known double neutron stars, one can expect the rate of mergers per galaxy to be 3–190 Myr⁻¹ (1 σ error range) with the mean being 13 Myr⁻¹ (Kim, Kalogera & Lorimer 2010). From the initial mass function and, hence, birth rate of massive stars that can become neutron stars, then taking into account the multiplicity rate, evolution and interaction of massive stars, one can predict 0.3–50 mergers per galaxy Myr⁻¹ (1 σ error range) with the mean being 15 Myr⁻¹ (Dominik et al. 2012). Thus, at most we expect 190 mergers per galaxy Myr⁻¹ or up to one merger in \sim 5263 yr. If such a merger would be observable as short GRB, one would have to correct the rate for the beaming fraction $f = 0.01$ – 0.13 for short GRBs (Rezzolla et al. 2011). For $f = 0.13$, one would then expect up to one merger in \sim 40 000 yr (within 1 σ error bars), pointed towards Earth as short GRB (10 times less within 4 kpc).

Because of sensitivity limits of observational techniques, both the observed multiplicity rate of massive stars and the estimated number of double neutron stars and mergers are lower limits. We can add the rates of mergers between neutron stars and black holes and between two black holes.

Neither the highly uncertain rates of observed short GRBs nor of neutron star mergers are consistent with the observed rate of the ¹⁴C event (one event in 3000 yr) within 1 σ , all are consistent within $\leq 2.6\sigma$. Furthermore, a short GRB is the only known phenomenon that can provide correct energetics, correct spectrum and correct time-scale for the observed event; it also does not produce a typical SN light curve for several months or a detectable SNR or a mass extinction event on Earth, which are all missing. If the AD 774/5 event was a short GRB and if the probability to observe one Galactic GRB within 3000 yr is too small, one would have to conclude that there are more (fainter) short GRBs than observed so far, and/or that there is another astrophysical population contributing to short GRBs, which was not yet fully recognized.

Short GRBs with extended emission may partly be due to either an accretion-induced collapse of a white dwarf or the merger of two white dwarfs (Berger 2011; Metzger et al. 2011; Bucciantini et al. 2012). In such an event, a magnetar can form (Bucciantini et al. 2012). The rate of mergers of two white dwarfs with a total mass above the Chandrasekhar mass limit of $\sim 1.4 M_{\odot}$ has been estimated to be $1.0^{+1.6}_{-0.6} \times 10^{-14}$ per M_{\odot} with 1 σ error bars (Badenes & Maoz 2012). This corresponds to only about one-tenth of the SN Ia rate, so that the merger of two white dwarfs with super-Chandrasekhar mass cannot explain all SN Ia events. However, it is suggested that such super-Chandrasekhar mergers can be observed as short GRBs (Berger 2011; Metzger et al. 2011; Bucciantini et al. 2012). For our Galaxy with $\sim 10^{11} M_{\odot}$, we obtain a rate of $3.0^{+4.8}_{-1.8}$ mergers of white dwarf binaries with super-Chandrasekhar mass in 3000 yr. If we assume that such an event can be observed as short GRB with extended emission with a beaming factor of up to $f = 0.25$ (Bucciantini et al. 2012), and if we also restrict the rate to the disc within 4 kpc (the maximum distance of a short GRB to explain the AD 774/5 event), we expect $0.08^{+0.12}_{-0.04}$ such mergers in 3000 yr. Since the error of the rate of ¹⁴C events (as in AD 774/5) is unconstrained, one cannot claim that the rates of white dwarf binary mergers with super-Chandrasekhar mass (pointing towards us as short GRB) and the ¹⁴C event rate are inconsistent.

Since short GRBs with extended emission may have lower total energies (Bucciantini et al. 2012), which can be below the BATSE and SWIFT sensitivity limits, they may often remain undetected, so that their observable rates could be underestimated. There is evidence for short GRBs with lower energies and their rate is prob-

ably much higher (Levan & Tanvir 2005; Tanvir et al. 2005; Nakar, Gal-Yam & Fox 2006). Given the discussion of the rates, we can speculate that some short GRBs, like possibly one in AD 774/5, are due to an accretion-induced collapse of a white dwarf or the merger of two white dwarfs, and that such (possibly frequent) short GRBs typically have energies below the current sensitivity limit of 10^{49} erg and possibly wide beaming angles; they may produce a neutron star, but no SNR.

4 CONCLUDING REMARKS

A long GRB can be accompanied by an SN and an SNR, but none were observed for AD 774/5; this could be due to strong absorption (no optical sighting of the SN) and large distance (faint SNR with very small angular extension on sky). With the typical isotropic equivalent energy output $E(\text{event}) = 10^{52}$ – 10^{54} erg of a long GRB in γ -rays of 10 keV to 30 GeV and $g = 0.1$ – 1 (Nakar 2007), we estimate its putative distance towards Earth from equation (1) to $d \simeq 1$ – 39 kpc, i.e. in our Galaxy or the neighbouring Canis Major, Sagittarius or Ursa Major II dwarf galaxies. To avoid a historical sighting of an SN brighter than $m \simeq 2$ mag (Strom 1994) at the minimum distance of 1 kpc, one would need an absorption of $A_V = 12.5$ mag for a peak absolute magnitude of $M \simeq -21$ mag for a collapsar/hypernova (Richardson et al. 2002). An area of 66 deg² has an absorption of $A_V \geq 12.5$ mag (Dobashi 2011), an even smaller area for clouds within 1 kpc. There is no such SNR detected behind these areas (Green 2009, footnote 1). Considering also that long GRBs are 20 times less frequent than short GRBs (Nakar 2007), a long GRB behind such strong absorption is then ≥ 12 727 times less likely than a short GRB to explain the ¹⁴C peak in AD 774/5. Moreover, sampling the whole observed range of spectral parameters of long GRBs with their smoothly broken power law or Band function (Band et al. 1993; Nakar 2007; Ghirlanda et al. 2009; Zhang et al. 2011), we cannot explain the differential ¹⁴C to ¹⁰Be production observed (Fig. 1). Hence, a short GRB remains the only plausible explanation for the ¹⁴C peak in AD 774/5.

We list in Table 1 all known neutron stars with characteristic age ≤ 25 000 yr (Manchester et al. 2005, footnote 2) at distances from 1 to 4 kpc, but without any known SNR (Green 2009, footnote 1). The list includes two Anomalous X-ray Pulsars (AXPs), one *Fermi* Gamma-ray Large Area Telescope pulsar (FGL) and one Soft Gamma-ray Repeater (SGR). We use a larger pulsar age upper limit (25 000 yr) than the time since AD 774/5 because characteristic ages are usually upper limits and can be 20 times larger than the true age (Kramer et al. 2003). We include SGR 0418+5729 with an upper limit for the period derivative and, hence, a lower limit on the age (which is below 25 000 yr). If a neutron star was formed in AD 774/5, it is also possible that it was

Table 1. Young neutron stars at 1–4 kpc without SNR. We list pulsar name with position for J2000.0, rotation/pulse period P , period derivative \dot{P} , distance and characteristic age $\tau = 1/2 \times (P/\dot{P})$, data from Manchester et al. (2005) or McGill SGR/AXP catalogue (footnote 2).

| Name (J2000.0) | Period P (s) | \dot{P} (s s ⁻¹) | Distance (kpc) | Age (kyr) | Remark |
|-------------------|-------------------|-----------------------------------|-------------------|--------------|--------|
| SGR 0418+5729 | 9.0784 | ≤ 0.0006 | ~ 2 | ≥ 24 | |
| PSR J1048–5832 | 0.1237 | $9.6\text{e-}14$ | 2.98 | 20.3 | FGL |
| PSR J1708–4009 | 11.0013 | $1.9\text{e-}11$ | 3.08 | 9.01 | AXP |
| PSR J1740–3015 | 0.6069 | $4.6\text{e-}13$ | 3.28 | 20.6 | |
| PSR J1809–1943 | 5.5404 | $7.8\text{e-}12$ | 3.57 | 11.3 | AXP |

not yet discovered, e.g. because of misdirected pulsar beaming, or that distance and/or age have not yet been determined. For the five pulsars listed here, one should obtain deep X-ray, γ -ray, $H\alpha$ and radio observations to search for SNRs: if an SNR can be excluded in one of them, that pulsar may be a good candidate for the product of the AD 774/5 event. Three of the five neutron stars listed are AXPs or SGRs, which can form by a short GRB with extended emission (Berger 2011; Metzger et al. 2011; Bucciantini et al. 2012).

In summary, all observables of the ^{14}C peak in AD 774/5 are consistent with a Galactic short GRB at 1–4 kpc: sufficient energetics, correct spectrum and correct time-scale, also neither an SN nor an SNR nor a mass extinction event. The only assumptions made were the following: from comparing their ^{14}C tree ring data with a model of incorporation of ^{14}C into the biosphere, M12 concluded that the event duration was one year or shorter, and they could then derive the ^{14}C flux and energy deposited on Earth which was also used in our work; we also used the ^{10}Be flux observed in the same decade (Horiuchi et al. 2008) and assumed that it was produced by the same event (see e.g. Stuiver et al. 1998) to derive the differential ^{14}C to ^{10}Be production rate; we derived a lower limit to the differential production rate because some of the ^{10}Be observed in that decade could have been produced by other effects. The derived lower limit was then found to be inconsistent with long GRBs, but fully consistent with the spectra of short GRBs. Rates of short GRBs and neutron star mergers are marginally consistent with one event in 3000 yr, but the error of the rate of the AD 774/5 event is unknown. The merger of two white dwarfs with super-Chandrasekhar mass or an accretion-induced collapse of a white dwarf producing a short GRB (with $\leq 10^{49}$ erg at ≤ 1 kpc) should also be considered. The product could be a neutron star without SNR, so that our conclusions are testable.

ACKNOWLEDGEMENTS

We would like to thank the German National Science Foundation DFG (Deutsche Forschungsgemeinschaft) for financial support through the collaborative research centre Sonderforschungsbereich SFB TR 7 Gravitational Wave Astronomy subproject C7. We used the online catalogue of Supernova Remnants by D. Green, the Chandra supernova remnant catalogue maintained by F. Seward, the ATNF online catalogue of pulsars maintained by G. B. Hobbs and R. N. Manchester, and the McGill online catalogue of SGRs and AXPs maintained by the McGill Pulsar Group. We also thank Kazuhito Dobashi for information about the size of the sky area, where the extinction is $A_V \geq 13$ or ≥ 12.5 mag, considering the whole sky.

REFERENCES

Badenes C., Maoz D., 2012, *ApJ*, 749, L11
Band D. et al., 1993, *ApJ*, 413, 281

Berger E., 2007, *ApJ*, 670, 1254
Berger E., 2011, *New Astron. Rev.*, 55, 1
Bibby J. L., Crowther P. A., Furness J. P., Clark J. S., 2008, *MNRAS*, 386, L23
Bucciantini N., Metzger B. D., Thompson T. A., Quataert E., 2012, *MNRAS*, 419, 1537
Burger G., Ebert H. G. (eds), 1981, *Proc. 4th Symp. Neutron Dosimetry*, Munich. Commission of the European Communities
Coward D. M. et al., 2012, *MNRAS*, 425, 2668
Dimbylow P. J., 1980, *Phys. Med. Biol.*, 25, 637
Dobashi K., 2011, *PASJ*, 63, 1
Dominik M., Belczynski K., Fryer C., Holz D. E., Berti E., Bulik T., Mandel I., O’Shaughnessy R., 2012, *ApJ*, 759, 52
Ghirlanda G., Nava L., Ghisellini G., Celotti A., Firmani C., 2009, *A&A*, 496, 585
Green D. A., 2009, *Bull. Astron. Soc. India*, 37, 45
Horiuchi K., Uchida T., Sakamoto Y., Ohta A., Matsuzaki H., Shibata Y., Motoyama H., 2008, *Quat. Geochronol.*, 3, 253
Hurley K. et al., 2005, *Nat*, 434, 1098
Kim C., Kalogera V., Lorimer D., 2010, *New Astron. Rev.*, 54, 148
Kramer M., Lyne A. G., Hobbs G., Löhmer O., Carr P., Jordan C., Wolszczan A., 2003, *ApJ*, 593, L31
Levan A., Tanvir N., 2005, *GCN Circ.*, 3927, 1
Lombardi M., Lada C. J., Alves J., 2008, *A&A*, 489, 143
Manchester R. N., Hobbs G. B., Teoh A., Hobbs M., 2005, *AJ*, 129, 1993 (updates available at <http://www.atnf.csiro.au/people/pulsar/psrcat>)
Melott A. L. et al., 2004, *J. Astrobiol.*, 3, 56
Metzger B. D., Berger E., 2012, *ApJ*, 746, 48
Metzger B. D., Giannios D., Thompson T. A., Bucciantini N., Quataert E., 2011, *MNRAS*, 413, 2013
Miyake F., Nagaya K., Masuda K., Nakamura T., 2012, *Nat*, 486, 240 (M12)
Nakar E., 2007, *Phys. Rep.*, 442, 166
Nakar E., Gal-Yam A., Fox D. B., 2006, *ApJ*, 650, 281
Pagani L. et al., 2004, *A&A*, 417, 605
Piran T., Nakar E., Rosswog S., 2012, preprint (arXiv:1204.6242)
Reipurth B., 2008, *Handbook of Low Mass Star Forming Regions*. Astron. Soc. Pacific, San Francisco
Rezzolla L., Giacomazzo B., Baiotti L., Granot J., Kouveliotou C., Aloy M. A., 2011, *ApJ*, 732, L6
Richardson D., Branch D., Casebeer D., Millard J., Thomas R. C., Baron E. A., 2002, *AJ*, 123, 745
Sadavoy S. I. et al., 2010, *ApJ*, 710, 1247
Strom R. G., 1994, *A&A*, 288, L1
Stuiver M. et al., 1998, *Radiocarbon*, 40, 1041
Tanvir N., Chapman R., Levan A., Priddey R., 2005, *Nat*, 438, 991
Thomas B. C. et al., 2005, *ApJ*, 634, 509
Zhang B. et al., 2011, *ApJ*, 730, 141

This paper has been typeset from a $\text{\TeX}/\text{\LaTeX}$ file prepared by the author.