A search for giant flares from soft gamma-repeaters in nearby galaxies in the Konus-Wind short burst sample

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ABSTRACT

The knowledge of the rate of soft gamma-ray repeater (SGR) giant flares is important for understanding the giant flare mechanism and the SGR energy budget in the framework of the magnetar model. We estimate the upper limit to the rate using the results of an extensive search for extragalactic soft gamma-repeater giant flares (GFs) among 140 short gamma-ray bursts detected between 1994 and 2010 by Konus-Wind using InterPlanetary Network (IPN) localizations and temporal parameters. We show that Konus-Wind and the IPN are capable of detecting GFs with energies of \(2.3 \times 10^{46}\) erg (which is the energy of the GF from SGR 1806−20 assuming a distance of 15 kpc) at distances of up to \(\sim 30\) Mpc and GFs with energies of \(<10^{45}\) erg (which is the energy of the GF from SGR 0526−66) at distances of up to \(\sim 6\) Mpc. Using a sample of 1896 nearby galaxies we found that only two bursts, GRB 051103 and GRB 070201, have a low chance coincidence probability between an IPN localization and a nearby galaxy. We found the upper limit to the fraction of GFs among short GRBs with fluence above \(\sim 5 \times 10^{-7}\) erg cm\(^{-2}\) to be \(<8\%\) (95% confidence level). Assuming that the number of active SGRs in nearby galaxies is proportional to their core-collapse supernova rate, we derived the one-sided 95% upper limit to the rate of GFs with energy output similar to the GF from SGR 1806−20 to be \((0.6−1.2) \times 10^{-5} Q_{46}^{-1.5}\) yr\(^{-1}\) per SGR, where \(Q_{46}\) is the GF energy output in \(10^{46}\) erg.

Key words: gamma-ray burst: general – stars: magnetars

1 INTRODUCTION

Soft gamma repeaters (SGRs) are thought to be a special rare class of neutron stars exhibiting two types of bursting emission in gamma-rays. During the active stage SGRs emit randomly occurring short (~ 0.01–1 s) hard X-ray bursts with peak luminosities of \(\sim 10^{38}−10^{42}\) erg s\(^{-1}\). The bursting activity may last from several days to a year or more, followed by a long quiescent period. Much more rarely, perhaps once during the SGR stage, an SGR may emit a giant flare (GF) with sudden release of an enormous amount of energy \(\sim (0.01−1) \times 10^{36}\) ergs. A GF displays a short \(~0.2−0.5\) s initial pulse of gamma-rays with a sharp rise and a more extended decay which evolves into a soft, long-duration decaying tail modulated with the neutron star rotation period; see Mererghetti (2013) for a detailed review.

To date, 15 SGRs have been discovered (Olausen & Kaspi 2014), 14 of which are in our Galaxy and one is located in the Large Magellanic Cloud (LMC). The first GF was detected from the LMC on March 5, 1979 by the Konus experiment on the Venera 11 and 12 interplanetary missions (Golenetskii et al. 1979; Mazets et al. 1979) as well as by the Interplanetary Network (IPN) (Barat et al. 1979; Cline et al. 1980; Evans et al. 1981; Cline et al. 1983). So far, only three GFs have been observed and all of them were detected by the Konus experiments and the IPN. Two recent GFs, from SGR 1900+14 and SGR 1806−20, were preceded by a pronounced increase in bursting activity (Mazets et al. 1999; Frederiks et al. 2007).

All of the known SGRs are rapidly spinning down X-ray pulsars with spin periods of 2–12 s and persistent X-ray luminosities of \(10^{35}−10^{36}\) erg s\(^{-1}\). The SGRs are thought to belong to a wider class of objects called magnetars. This class also includes anomalous X-ray pulsars (AXPs) and high-B radio pulsars; a recent catalogue lists 26 objects in the magnetar class (Olausen & Kaspi 2014). The distinction between AXPs and SGRs is blurred due to the detection of anomalously high quiescent X-ray luminosity of SGRs and the occasional bursting of AXPs. About half of the known magnetars are associated with star forming regions or SNRs and appear to be young isolated NS. The spatial distribution of magnetars provides evidence that they are born from the most massive O stars (Olausen & Kaspi 2014). It is believed that the activity of magnetars is related...
to the presence of a superstrong magnetic field $\sim 10^{13}-10^{15}$ G, inferred from the high spin down rate and other evidence (Duncan & Thompson 1992; Thompson & Duncan 1994, 1996). The first direct measurement of the high spin down rate of SGR 1806–20 by Kouveliotou et al. (1998) gave strong support to the magnetar nature of SGRs.

Due to the enormous luminosity of the initial pulse GFs can be detected from SGRs in nearby galaxies. In this case, the initial pulse will be indistinguishable from a short gamma-ray burst (GRB). The rate of soft gamma-ray repeater GFs and their fraction among short-duration GRBs are important quantities for the understanding of the giant flare mechanism in the framework of the magnetar model. A limit on the fraction of SGR GFs among short GRBs was estimated in several studies [Lazzati, Ghirlanda & Ghisellini 2005; Nakar et al. 2006; Palmer et al. 2004; Popov & Stern 2004; Ofek 2005] to be $\sim 1–15\%$; see Hurley (2011) for a detailed review. Two extragalactic GF candidates have been reported and localized by the IPN: GRB 051103 in the the M81/M82 group of galaxies (Ofek et al. 2006; Frederiks et al. 2007a; Hurley et al. 2010) and GRB 070201 in the Andromeda galaxy (Mazets et al. 2008; Ofek et al. 2008). However, Hurley et al. (2010) argued that GRB 051103 is unlikely to be an SGR giant flare in the nearby Universe, mostly due to its extreme peak luminosity of approximately $4.7 \times 10^{46}$ erg s$^{-1}$, assuming it was from an SGR in the M81/M82 group, which is a factor of 10 brighter than the peak luminosity of the giant flare from SGR 1806–20, which is $(2–5) \times 10^{46}$ erg s$^{-1}$ assuming a distance of 15 kpc.

A recently published catalogue of IPN localizations of Konus-Wind short GRBs [Pal’shin et al. 2013] contains localizations of 271 short GRBs detected by Konus-Wind during its almost 16 yrs of continuous full-sky observations. This catalogue allows us to search for GF candidates in the largest well-localized short GRB sample.

In Section 2 we discuss the Konus-Wind and IPN sensitivity to GFs. In Section 3 we provide a nearby galaxy sample and discuss its properties. We present in Section 4 the search for Konus-Wind short GRBs that spatially coincide with the nearby galaxies and estimate the fraction of GFs among short GRBs. In Section 5 we use results of this search to derive upper limits on the GF rate. Finally, in Section 6 we give concluding remarks.

2 THE KONUS-WIND AND IPN SENSITIVITY TO GIANT FLARES

The Konus-Wind instrument (Aptekar et al. 1993) consists of two identical omnidirectional NaI(Tl) detectors. The detectors are mounted on opposite faces of the rotationally stabilized Wind spacecraft. Each detector has an effective area of $\sim 80–160$ cm$^2$ depending on the photon energy and incidence angle. Konus-Wind has two operational modes: background and triggered. The triggered mode is initiated when the number of counts on one of two fixed time scales, 1 s or 140 ms, exceeds a preset value. This value is defined in terms of a number of standard deviations above the background ($\approx 9\sigma$). There is a single background measurement period of 30 s duration before the trigger interval. The initial pulse of a GF from a distant galaxy can trigger Konus-Wind on the 140 ms time scale.

Among the three detected GFs, only one, from SGR 1806–20, has well estimated initial pulse spectral parameters. The parameters were derived using the detection of the flare radiation reflected from the Moon [Frederiks et al. 2007a]. The initial pulse spectrum of this GF is well described by a power law with an exponential cutoff $(dN/dE \sim E^{-\alpha} \exp(-E/E_0))$ with $\alpha = 0.73 \pm 0.64$ and $E_0 = 666_{-360}^{+1800}$ keV (or the $\nu F_{\nu}$ spectrum peak energy $E_p = (2 - \alpha)E_0 = 850_{-120}^{+1259}$ keV), see also Terasawa et al. (2005). Two other GFs are characterized by only rough estimates of $E_p$: $\sim 400–500$ keV (SGR 0526–66, Golenetskii et al. 1979; Mazets et al. 1979) and $> 250$ keV (SGR 1900+14, Hurley et al. 1999; Mazets et al. 1999a).

Assuming all the initial pulse energy is released during the short trigger timescale (140 ms), we calculated the minimum fluence $S_{\text{min}}$ in the 20–10000 keV band which produces a 9$\sigma$ increase in the count rate in the 50–200 keV energy range using forward folding of an incident photon spectrum through the detector response matrix. For calculations we used an average background count rate of 400 counts s$^{-1}$ in the 50–200 keV energy range.

We found that $S_{\text{min}}$ strongly depends on the burst spectral hardness ($E_p$ and $\alpha$). The known $E_p$ range of about 200–1000 keV corresponds to $S_{\text{min}} = (2.1–5.7) \times 10^{-7}$ erg cm$^{-2}$ (Fig. 1). Then, the corresponding limiting detection distance was calculated as $d_{\text{max}} = \sqrt{Q/(4\pi S_{\text{min}})}$, where $Q$ is the GF energy output.

The IPN (Hurley et al. 2013) is a set of gamma-ray detectors on board several spacecraft orbiting the Earth, Mars and Mercury. The IPN allows near continuous, all-sky coverage and provides accurate sky locations determined by triangulation between the spacecraft in the network using GRB photon arrival times. Each pair of spacecraft constrains the intergalactic parameters. The parameters were derived using the intersection of two or more annuli forms an error box. Depending upon the spacecraft involved, the error box areas can vary from square arcminutes to thousands of degrees.

We investigated the dependence of the IPN error box area on the Konus-Wind fluence (20–10000 keV) over the 140 ms interval with the highest count rate and found no prominent correlation (Fig. 2). So the IPN sensitivity to short GRBs in terms of the error box area does not depend on the Konus-Wind burst fluence. Therefore $S_{\text{min}}$ can be taken as the IPN sensitivity to short GRBs.

The distance estimates for SGR 1806–20 range from about 6 kpc to 19 kpc [Tendulkar, Cameron & Kulkarni 2012; the most recent analysis of Svirsaki, Nakar & Ofek 2011] gives the range 9.4–18.6 kpc. The isotropic energy release of the initial pulse of the GF from SGR 1806–20 ($Q = (2.3 \times 10^{46}d_1^2)$ erg) implies a limiting distance $d_{\text{max}} = (18–30) \times d_1$ Mpc, where $d_1$ is the distance to SGR 1806–20. The range of $d_{\text{max}}$ corresponds to the $S_{\text{min}}$ range. Less intense GFs with $Q \approx 1 \times 10^{45}$ erg (like the 1979 March 5 GF from SGR 0526–66) can be detected up to $d_{\text{max}} = (3.8–6.3)Q_{15}^{1/3}$ Mpc, where $Q_{15}$ is the GF energy output in $10^{45}$ erg.
3 THE GALAXY SAMPLE

The Gravitational Wave Galaxy Catalogue (GWGC, White, Daw & Dhillon 2011) contains over 53,000 galaxies within 100 Mpc. Our initial sample includes 8112 of them within a distance 30 Mpc. The distance uncertainty in the sample ranges from 15% to 22%. Using the method suggested by Ofek (2007), we estimate the completeness of the galaxy sample due to obscuration by the Galactic plane to be \( \epsilon_L = 90\% \). Among the 7322 galaxies with a given \( L_B \), 2405 have an unknown morphological type. These galaxies are, on average, about three magnitudes dimmer than those with a given type and they contain less than 7% of the cumulative supernova rate, so we do not take them into account. Then we limited our final sample to 1896 galaxies with the highest rate which contain \( \epsilon_{SN} = 90\% \) of the cumulative rate and have morphological types other than E and S0. The sky surface density of these galaxies is 0.046 deg\(^{-2}\). The cumulative supernova rate for this sample is \( R_{SN} = 22.8 \pm 0.4 \) yr\(^{-1}\).

We compared the estimated volumetric \( R_{SN} \) for the 1896 galaxies with the lower limit for the local CCSN rate (distances up to 15 Mpc) derived by Mattila et al. (2012) which is \( 1.9^{+0.4}_{-0.2} \times 10^{-4} \) yr\(^{-1}\) Mpc\(^{-3}\). The volumetric \( R_{SN} \) is shown in Fig. 3. The volumetric \( R_{SN} \) from the blue galaxy luminosity is consistent within 1\( \sigma \) with the observed CCSN rate assuming that \( \approx 19\% \) of local CCSN were missed by the optical surveys. The volumetric CCSN rate shows a decline beyond ~ 22 Mpc. The decline could be the result of observational selection effects, therefore we used the volumetric CCSN rate averaged over the distance range up to 22 Mpc, which is \( (2.74 \pm 0.18) \times 10^{-3} \) Mpc\(^{-3}\) (1\( \sigma \) CL), as an estimate of the CCSN rate at larger distances.

We also found an excess in the volumetric CCSN rate within ~ 10 Mpc up to \((9.3 \pm 1.6) \times 10^{-4} \) yr\(^{-1}\) Mpc\(^{-3}\) (1\( \sigma \) CL) within 5.1 Mpc, with only five galaxies containing 25% of the total CCSN rate: PGC047885 at \( d = 5 \) Mpc, IC 0342 at 3.28 Mpc, NGC 6946 (Fireworks Galaxy) at 5.9 Mpc, NGC 5457 (Pinwheel Galaxy, M101) at 6.7 Mpc, and NGC 5194 (Whirlpool Galaxy, M51) at 5.9 Mpc. These galaxies are the best sites to search for extragalactic GFs in addition to the previously mentioned galaxies: M82 at \( d = 3.4 \) Mpc, NGC 253 (Sculptor Galaxy) at 2.5 Mpc, NGC 4945 at 3.7 Mpc, and M83 at 3.7 Mpc (Popov & Sterl 2006).

4 THE SEARCH FOR SGR GIANT FLARES IN THE KONUS-WIND SHORT GRB SAMPLE

The Pal’shin et al. (2013) catalogue contains IPN localizations for 271 out of the 296 Konus-Wind short GRBs with a duration \( T_{50} \leq 0.6 \) s (Svinkin et al. 2014). This sample contains 23 GRBs classified as short GRBs with extended emission (EE). These bursts were observed by at least one IPN spacecraft, enabling their localizations to be constrained by triangulation. We limit our search to 140 bursts with IPN error box area less than 10 deg\(^2\) and search for overlaps between each IPN box and galaxies from our sample. In the search a galaxy is modelled, following Ofek (2007), by a circle determined by the galaxy’s major diameter from GWGC.

We found that 12 out of the 140 IPN error boxes, with a total area of 217 deg\(^2\), overlap 20 galaxies (none of the localizations of short GRBs with EE contains a galaxy).
This number is lower than that expected for chance coincidences calculated for the 140 IPN boxes (22–44 galaxies at 95% CL). The confidence interval was calculated using the bootstrap approach, creating 1000 random realizations of the galaxy sample and counting the number of overlaps with the IPN boxes list for each realization. We used the 25th and 975th ranked values as the 95% confidence interval boundaries.

Only one of these error boxes (GRB20050312_T2041) overlaps the outskirts of the Virgo cluster, but the box does not contain any galaxy from our sample. The cluster was modelled with a circle centred at R.A. = 188º, Dec. = 12º, whose radius is 6º using the cluster parameters from Binggeli, Tammann & Sandage (1987).

We found that only two previously reported GF candidates, GRB 051103 associated with the M81/M82 group of galaxies (error box area 4.3 × 10⁻³ deg²) and GRB 070201 associated with the Andromeda galaxy (error box area 0.123 deg²), have low probabilities of chance coincidence (P_chance ≲ 1%). P_chance is the probability to find at least one galaxy in the given IPN error box. The probability was calculated in the same way as the confidence interval.

We then applied the search procedure to the sample of 98 bursts with IPN error box area less than 1 deg² (Pal'shin et al. 2013) which contains short GRBs observed by at least one distant spacecraft. We found that only the localizations of the two above-mentioned bursts contain galaxies.

A common feature of all known GFs is the short duration of the initial peak, ≲ 500 ms, and the short rise time, tᵣ ≲ 25 ms. Among 296 Konus-Wind short GRBs 40 have tᵣ < 25 ms and a duration < 500 ms. The previously discussed GF candidates GRB 051103 and GRB 070201 have tᵣ = 2 ms and tᵣ = 24 ms, respectively. We then limited our search to 17 of these bursts with IPN error box area less than 10 deg².

We found that four out of the 17 IPN boxes, with a total area of 47 deg², contain five galaxies. This number is consistent with that expected for chance coincidences calculated for this sample: 5–16 galaxies (95% CL). Among these four bursts only GRB 051103 and GRB 070201 have low probabilities of chance coincidence. The results for all burst samples are summarized in Table I.

Given the product of the completeness factors e_{GL} e_{SN} ≳ 76%, and assuming that the search yielded two GF candidates among 98 well localized Konus-Wind short GRBs, the upper limit to the fraction of GF among Konus-Wind short GRBs is less than 8% (≈ 6.296/98/0.76) at a one-sided 95% CL (Gehrels 1986). Due to the whole sky coverage of the IPN this limit can be adopted for all short GRBs with fluences above ∼ 5 × 10⁻⁷ erg cm⁻². The resulting upper limit is stricter than the limit obtained in Ofek (2007).

5 THE LIMITS ON THE GIANT FLARE RATE

Assuming that only one GF with energy output Q ≥ 10⁴⁶ erg has been observed, in the M81/M82 group of galaxies, within a volume d ≤ 30 Mpc, it is possible to calculate an upper limit to the rate of such GFs.

We assume that the number of active SGRs (N_{SGR}(d)) in the galaxies within distance d is proportional to the core-collapse supernova rate R_{SN}(d) = 1/3πd³r_{SN}, where r_{SN} is the volumetric CCSN rate.

\[
N_{SGR}(d) = \frac{N_{SGR,MW,LMC}}{R_{SN,MW,LMC}} R_{SN}(d). \tag{1}
\]

The Galactic CCSN rate is R_{SN,MW} = 0.028 ± 0.006 yr⁻¹ with a systematic uncertainty of a factor of ∼ 2 (Li et al. 2011) and the LMC rate is R_{SN,LMC} = 0.013 ± 0.009 yr⁻¹ (van den Bergh & Tammann 1991). Hence the total CCSN rate in MW and LMC is R_{SN,MW,LMC} = 0.041 ± 0.011 yr⁻¹.

The observed rate of GFs per SGR is given by a simplified version of eq. 3 from Ofek (2007):

\[
R_{GF} = \frac{N_{GF,obs}}{\Delta T N_{SGR}(d_{max})} \tag{2}
\]

where N_{GF,obs} is the number of observed GF, ΔT = 16 yr is the Konus-Wind observation time, and N_{SGR}(d) is given by eq. 1. To estimate an upper limit to R_{GF} in case of one observed GF we used the 95% one-sided upper limit of N_{GF,obs} = 4.744 (Gehrels 1986).

For the rate of GFs with energy output Q ≥ 10^{44} erg eq. 2 gives an upper limit of (0.6–1.2) × 10⁻⁴ Q_{46}⁻¹.5 yr⁻¹ SGR⁻¹, where Q_{46} is a GF energy output in 10^{46} erg. The detection of only one GF with energy output Q ≥ 10^{46} erg in the last 35 yr (since 1979) from SGR 1806–20 implies that the Galactic rate is (0.005–1) × 10⁻² yr⁻¹ SGR⁻¹ (≈ 1.0–9.8/35/15) at the one-sided 95% CL. This value is consistent with the upper limit derived above for the SGR 1806–20 distance 9.4–18.6 kpc, primarily due to the large uncertainties in both the upper limit and the Galactic GF rate.

For less energetic flares with energy output Q ≤ \(10^{43} \text{erg}\), we found four among the 98 well localized Konus-Wind short GRBs, which have low probabilities of chance coincidence. The results for all burst samples are summarized in Table I.

1 See the burst details in Pal’shin et al. (2013).
10^{45} erg which can be detected by Konus-Wind at distances up to 6.3 Mpc, assuming one such flare was detected from the Andromeda galaxy, the implied rate upper limit is \((0.9–1.7) \times 10^{-3} \text{ yr}^{-1} \text{ SGR}^{-1}\) (95\% CL). This limit is consistent with the observed Galactic rate of \((0.05–1.4) \times 10^{-2} \text{ yr}^{-1} \text{ SGR}^{-1}\) (95\% CL).

6 SUMMARY AND DISCUSSION

We have estimated the Konus-Wind and IPN sensitivity to GFs and derived the limiting detection distance for GFs similar to that from SGR 1806–20 to be \((18–30)d_{15}\) Mpc. Less energetic flares such as those from SGR 1900+14 and SGR 0526–66 can be detected by Konus-Wind and IPN from galaxies at \(d \leq 6\) Mpc. We searched for Konus-Wind short GRBs that spatially coincide with galaxies within 30 Mpc and have found that only two previously reported GF candidates have a low chance coincidence probability: GRB 051103 and GRB 070201 localized by the IPN in the M81/M82 group of galaxies and the Andromeda galaxy, respectively. We have not found any candidate GF from the Virgo cluster. Assuming only one GF with energy output \(Q \geq 10^{46}\) erg was observed in the M81/M82 group of galaxies within the volume \(d \leq 30\) Mpc we obtain an upper limit to the rate of such flares to be \((0.6–1.2) \times 10^{-4}Q_{46}^{1.5} \text{ yr}^{-1} \text{ SGR}^{-1}\) per SGR, where \(Q_{46}\) is the GF energy output in \(10^{46}\) erg. This limit was calculated using the largest sample of well localized short GRBs and is consistent with the finding of Ofek (2007). The limit implies roughly one giant flare with energy output \(Q \geq 10^{46}\) erg during the lifetime of an SGR, \(10^{3}–10^{7}\) yr.

For a GF with energy output of the order of the 5 March 1979 event \((Q \lesssim 10^{45}\) erg) the implied rate is nearly an order of magnitude higher \((0.9–1.7) \times 10^{-3} \text{ yr}^{-1} \text{ SGR}^{-1}\) (95\% CL). This can be interpreted to mean that more than one such GF can be observed during SGR lifetime. The measured dipolar magnetic fields of SGR 1900+14 and SGR 0526–66, \(5.6 \times 10^{3} \text{ G}\) and \(7 \times 10^{14} \text{ G}\), respectively (Olausen & Kaspi 2014), seem to be sufficient to power a dozen GFs with \(Q \sim 10^{45}\) erg.

The upper limits we have presented contain uncertainties of about an order of magnitude which account for the uncertainty in the Galactic CCSN rate and the limiting detection distance of the IPN.

We found galaxies which are promising targets for GF observations: PGC047885, IC 0342, NGC 6946, NGC 5457, and NGC 5194, in addition to those discussed in Popov & Sterzi (2006).

We also derived the upper limit to the rate of bright GFs using Swift-BAT data. Since its launch in November 2004 Swift has observed only one candidate extragalactic GF, GRB 050906 [Levan et al. 2008], with a suggested host IC 328 at \(\approx 130\) Mpc. This burst had the lowest fluence in the 15–150 keV band of all the reported GRBs, \(S_{\text{min}} = 6.1 \times 10^{-9}\) erg \(\text{cm}^{-2}\) [Sakamoto et al. 2011], and a soft spectrum described by a power law model with a photon index of \(-1.7\). The extrapolated energy output of the GF from SGR 1806–20 from 20 keV–10 MeV to 15–150 keV using a cutoff power law model with \(\alpha = -0.73\) and \(E_p = 850\) keV yields \(2.5 \times 10^{45}\) erg, which corresponds to a limiting distance of 60 Mpc. The interpretation of GRB 050906 as an SGR giant flare in IC 328 is unlikely due to the derived Swift-BAT limiting detection distance.

The BAT 90\% sky exposure time during 2004–2010 was \(7.25 \times 10^6\) s (0.23 yrs) [Baumgartner et al. 2013], and extrapolation of this value to 2004–2013 gives 0.35 yrs. The non-detection of a GF in the volume \(d \leq 60\) Mpc during Swift-BAT operations implies a one-sided 95\% CL upper limit for a GF with this energy output to be \(6 \times 10^{-4}Q_{45}^{1.5} \text{ yr}^{-1} \text{ SGR}^{-1}\), where \(Q_{45}\) is the GF energy output in \(10^{45}\) erg in the 15–150 keV band. Despite BAT’s high sensitivity this upper limit is less strict than that obtained using Konus-Wind and IPN data due to a lower period of whole sky observations. Nevertheless the Swift-BAT is a very promising mission to detect extragalactic SGR giant flares.

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