First intermediate flare from SGR 1935+2154

A V Kozlova¹, G L Israel², D S Svinkin¹ and D D Frederiks¹

¹ Ioffe Institute, 26 Polytekhnicheskaya, St. Petersburg, 194021, Russia
² INAF - Osservatorio Astronomico di Roma, via Frascati 33, I- 00040 Monteporzio Catone, Roma, Italy

E-mail: ann_kozlova@mail.ioffe.ru

Abstract. The first intermediate flare from newly discovered SGR 1935+2154 was detected and localized by four Interplanetary network (IPN) spacecraft on 2015 April 12. Among the observing instruments, only Konus-Wind gamma-ray burst spectrometer (KW) was able to measure high-resolution light curves and multi-channel energy spectra of the flare. We report on the results of temporal and spectral analyses of the KW data, the flare energetics, a search for Quasi-Periodic Oscillations in the light curve, and, finally, discuss the source distance estimate based on the distribution of double blackbody spectral fit parameters.

1. Introduction

Observations of Soft Gamma Repeaters (SGRs) have already more than 30 years of history. They were discovered through the detection of recurrent short (\(\sim 0.1\) s) bursts of hard X-rays/soft Gamma-rays by the Konus instrument aboard the Venera 11-14 spacecraft. The first bursts were initially classified as a subtype of gamma-ray bursts (GRB), one with a short duration and a soft spectrum [1].

Up to now, we know that such numerous short bursts, with a total energy release \(E_{\text{tot}}\) of \(\sim 10^{38} - 10^{40}\) erg, are the most common manifestation of SGR bursting activity, but there are two other, more rare types of bursts emitted by SGRs: giant flares and intermediate bursts. The extraordinary giant flares are the most intense Galactic events. They are characterized by short, hard initial pulse having a huge energy release of \(\sim 10^{44} - 10^{46}\) erg followed by a long-duration decaying tail modulated with the neutron star rotation period. So far, only three giant flares have been observed from three out of the fifteen confirmed SGRs [2] on 1979 March 5, 1998 August 27 and 2004 December 27. The high-fluence intermediate bursts are intermediate in terms of duration, peak luminosity and energy between the short bursts and the giant flares. Such events are characterized by durations of few seconds–few tens of seconds; the brightest of them have \(E_{\text{tot}}\) up to \(\sim 5 \times 10^{42}\) erg [3], less than that of the giant flare, though orders of magnitude larger than that of the most common short SGR bursts. Only a few dozen intermediate bursts are known to date and properties of such outstanding events are of special interest.

The soft gamma-ray repeater SGR 1935+2154 was discovered on 2014 July 5 through a series of three short bursts [4], detected by the Swift/BAT. Several days later, its persistent pulsating X-ray counterpart was discovered by the Chandra X-ray Observatory [5] with a pulse period of \(\sim 3.2\) s. The location of the SGR as determined by Swift/XRT [4] sits very close to the geometric centre of the Galactic supernova remnant (SNR) G57.2+0.8 [6] with known distance of about 9.1 kpc [7]. In 2015 February Fermi/GBM and Swift/BAT observed a weak burst
activity from the source — the first one since the discovery. More recently, the first intermediate flare from SGR 1935+2154 was detected and localized by four Interplanetary network (IPN) spacecraft [8]: INTEGRAL, Wind, Mars-Odysey, and MESSENGER. Among the observing instruments, only Konus-Wind gamma-ray burst spectrometer (KW) [9] was able to measure high-resolution light curves and multi-channel energy spectra of the flare.

The rest of this paper is organized as follows. In Section 2, we present results of the KW timing analysis and detailed spectroscopy. We report on the search for Quasi-Periodic Oscillations (QPOs) in the light curve in Section 3. Finally, in Section 4, we conclude with a few remarks, compare our results to the previous ones derived for the short and intermediate bursts from different SGRs and discuss the source distance estimate based on the distribution of double blackbody spectral fit parameters.

2. Data analysis

The SGR burst triggered detector S2 of the Konus-Wind γ-ray spectrometer at \( T_0 = 41064.683 \) s UT (11:24:24.683) on 2015 April 12. The burst time histories were recorded in three energy bands: G1 (20–80 keV), G2 (80–300 keV), and G3 (300–1200 keV) with a time resolution of 2 ms from \( T_0 - 0.512 \) s to \( T_0 + 0.512 \) s and of 16 ms afterwards.

As observed by Konus-Wind, the burst light curve shows a single pulse which starts at \( \sim T_0 - 0.062 \) s with a sharp (\(<10\) ms) rise and decays to background level at around \( T_0 + 1.680 \) s. The total burst duration \( T_{100} = 1.742 \) s was determined at the 5σ level in the G1+G2 energy band (20–300 keV). The corresponding values of \( T_{90} \) and \( T_{50} \) defined as the times during which 90 % and 50 % of the total burst counts have been accumulated are \( 1.412 \pm 0.016 \) s and \( 0.654 \pm 0.016 \) s, respectively. The start of the \( T_{90} (T_{50}) \) interval specified by the time at which 5 % (25 %) of the total counts have been reached. The time history of the burst is shown in Figure 1.

![Figure 1](image1.png)

**Figure 1.** Time history of the SGR burst recorded by Konus-Wind in the 20–1200 keV energy range with 16 ms resolution. The count rates are dead-time corrected; the dashed line indicates the background level. The vertical dotted lines denote the intervals over which the time-resolved spectra 1–7 were accumulated. 7' represent a 0.32 s-long part of spectrum 7, which contains \( \sim 90\% \) of counts in this spectrum.

![Figure 2](image2.png)

**Figure 2.** Power spectrum produced from the KW light curve in the G1+G2 energy range (upper panel). Curves representing the upper limits to the non-detection of pulsations are in the lower panel. The two horizontal dashed lines represent the 10 % and 50 % upper limits to the pulsed fraction. Lines of different colours correspond to the different time resolutions.
During the burst the instrument measured seven multichannel energy spectra covering a wide energy range from 20 keV to 14 MeV; for the spectra accumulation intervals see Table 1. The raw count rate spectra were rebinned in order to have at least 10 counts per energy bin, and fitted using XSPEC, version 12.8 [10]. We use only the 20 to 250 keV fitting interval since no emission was detected at a higher energies. The spectral analysis was performed by applying two spectral models, which have been shown to be the best-fits to the broadband spectra of SGR bursts (e.g. [11, 12, 13, 14]). The first one is a sum of two blackbody functions with the normalization proportional to the surface area (bbodyrad+bbodyrad in XSPEC; abbreviated as 2BB model throughout this paper). The second model is a power law with an exponential cutoff (CPL), parametrized as $F(E) \propto E^{-\alpha} \exp(-2(\alpha+1)E/E_p)$, where $E_p$ is the peak energy in the $\nu F_\nu$ spectrum. We also tried to fit the spectra to a single blackbody function and found that this model may be rejected on statistical grounds ($\chi^2 = 288/32$ dof for time-integrated spectrum).

A summary of the Konus-Wind spectral fits is presented in Tables 1 and 2. The time-integrated spectrum is best fitted with the CPL model ($\chi^2 = 32.4/31$ dof) with an index $\alpha$ of $\sim 0.2$ and $E_p \approx 36$ keV. The 2BB model applied to this spectrum also yields a reasonably good fit ($\chi^2 = 37/30$ dof). The temperatures of the cool and hot BB components are $kT_1 \approx 6.4$ and $kT_2 \approx 12.4$ keV, and the corresponding radii of the emitting areas (calculated at the distance of 9.1 kpc) are $R_1 \approx 19.4$ km and $R_2 \approx 6.0$ km, respectively. The low-kT BB contribution to the total flux in the 20–200 keV range is about 27%. We note that since no burst emission was detected after $T_0 + 1.680 \text{ s}$, the 2BB model normalizations for spectrum 7 and the time-integrated spectrum are calculated using intervals 1.280–1.680 s and 0.0–1.680 s, respectively. The time-resolved spectral analysis using the 2BB model shows significant variation of the parameters during the burst, while the variations of the CPL model parameters do not differ much from those found for the time-integrated spectrum.

From the CPL spectral fits, we estimate the total energy fluence of the burst S to be $(2.50 \pm 0.03) \times 10^{-5}$ erg cm$^{-2}$ and the peak energy flux $F_{\text{max}}$ to be $(2.15 \pm 0.13) \times 10^{-5}$ erg cm$^{-2}$ s$^{-1}$ in a 16 ms time interval starting at $T_0 + 0.800 \text{ s}$. Both values are measured in the 20–200 keV

### Table 1. 2BB model spectral fit results (in the 20–250 keV band). $R_{km}$ is the radius of the emitting region in km and $D_{10}$ is the distance to the source in units of 10 kpc. Errors are quoted at the 68% confidence level.

| Spectra | Accumulation interval (keV) | $kT_1$ (keV) | $R_{km}^2/D_{10}^2$ | $kT_2$ (keV) | $R_{km}^2/D_{10}^2$ | $\chi^2$/dof |
|---------|----------------------------|-------------|---------------------|-------------|---------------------|--------------|
| 1       | 0.0 –0.064                 | 7.7$^{+0.8}_{-1.1}$ | 299$^{+123}_{-70}$ | 14.9$^{+5.9}_{-2.6}$ | 8.2$^{+14.5}_{-7.1}$ | 4.8/15       |
| 2       | 0.064–0.128                | 6.3$^{+0.9}_{-1.1}$ | 621$^{+486}_{-202}$ | 13.1$^{+1.9}_{-2.1}$ | 25.1$^{+29.3}_{-17.9}$ | 8.3/15       |
| 3       | 0.128–0.192                | 4.5$^{+1.0}_{-1.0}$ | 1830$^{+3730}_{-986}$ | 10.7$^{+0.9}_{-0.6}$ | 88.9$^{+36.8}_{-32.6}$ | 15.0/15      |
| 4       | 0.192–0.256                | 8.4$^{+1.1}_{-1.6}$ | 246$^{+134}_{-56}$ | 14.1$^{+14.1}_{-2.8}$ | 12.7$^{+32.1}_{-12.5}$ | 8.4/15       |
| 5       | 0.256–0.768                | 5.4$^{+0.9}_{-0.8}$ | 769$^{+571}_{-260}$ | 11.6$^{+0.5}_{-0.3}$ | 93.1$^{+20.3}_{-22.9}$ | 29.3/26      |
| 6       | 0.768–1.280                | 7.0$^{+0.4}_{-0.6}$ | 449$^{+108}_{-72}$ | 13.6$^{+0.9}_{-0.6}$ | 32.9$^{+14.0}_{-11.5}$ | 36.4/28      |
| 7       | 1.280–9.472a               | 7.7$^{+0.6}_{-1.0}$ | 165$^{+23}_{-60}$ | 14.3$^{+3.4}_{-2.0}$ | 3.7$^{+7.8}_{-2.0}$ | 23.2/30      |
| 1–7     | 0.0 –9.472a                | 6.4$^{+0.4}_{-0.4}$ | 455$^{+73}_{-55}$ | 12.4$^{+0.4}_{-0.4}$ | 43.5$^{+8.8}_{-8.1}$ | 37.0/30      |

$^a$ The model normalizations for spectra 7 and 1–7 are calculated using intervals 1.280 – 1.680 s and 0.0 – 1.680 s, respectively.
Table 2. CPL model spectral fit results (in the 20–250 keV band). Errors are quoted at the 68 % confidence level.

| Spectra | Accumulation interval (keV) | $\alpha$ | $E_p$ (keV) | $\chi^2$/dof |
|---------|-----------------------------|---------|-------------|-------------|
| 1       | 0.0 –0.064                  | $0.25_{-0.42}^{+0.46}$ | $34.3_{-1.9}^{+1.6}$ | 6.9/16     |
| 2       | 0.064–0.128                 | $-0.38_{-0.32}^{+0.35}$ | $31.2_{-2.7}^{+2.2}$ | 8.1/16     |
| 3       | 0.128–0.192                 | $-0.13_{-0.37}^{+0.39}$ | $30.9_{-2.4}^{+2.0}$ | 16.4/16    |
| 4       | 0.192–0.256                 | $0.70_{-0.40}^{+0.43}$ | $37.4_{-1.4}^{+1.3}$ | 8.8/16     |
| 5       | 0.256–0.768                 | $0.37_{-0.12}^{+0.12}$ | $37.3_{-0.5}^{+0.5}$ | 26.7/27    |
| 6       | 0.768–1.280                 | $0.05_{-0.12}^{+0.12}$ | $37.5_{-0.6}^{+0.6}$ | 31.0/29    |
| 7       | 1.280–9.472                 | $0.75_{-0.43}^{+0.46}$ | $32.9_{-1.2}^{+1.1}$ | 25.8/31    |
| 1–7     | 0.0 –9.472                  | $0.20_{-0.08}^{+0.08}$ | $35.7_{-0.3}^{+0.3}$ | 32.4/31    |

energy range and quoted errors are at the 90 % confidence level. Assuming isotropic emission and the distance to the source of 9.1 kpc, the total energy release in the burst $E_{\text{tot}}$ is $\sim 2.5 \times 10^{41}$ erg and the peak luminosity, $L_{\text{max}}$, $\sim 2.1 \times 10^{41}$ erg s$^{-1}$.

3. Search for QPOs
Quasi-periodic oscillations discovered in soft-gamma repeaters [15, 16, 17] are expected to help us to study the properties of matter in neutron stars. Through detection of the frequencies of neutron star oscillations, it might be possible to deduce neutron star masses and radii, the equation of state, and so on (e.g., [18, 19]).

We searched for pulsations in the data total energy range by using the Fast Fourier Transform method without finding any statistically significant signal. Following the recipe described in [20] we derived the upper limits on the pulsed fraction at a 3$\sigma$ confidence level of $>50\%$ for frequencies in the 5–60 Hz range and 10–30% between 60 and 250 Hz. The results are presented in Figure 2.

4. Discussion
We have carried out a detailed study of the spectral and temporal properties of the first intermediate burst from the recently discovered SGR 1935+2154 observed by Konus-Wind. The rather long duration of the burst along with the large measured energy fluence put it in the class of “intermediate” SGR bursts. We found that the burst spectra in the 20–250 keV energy range are fitted well by both CPL and two-component 2BB models. Previously, these two models were successfully used to describe the SGR bursting emission over broad energy ranges. The temperatures and radii we obtained for the 2BB model are similar to those of other SGR sources ($kT_1 \sim 3–7$ keV, $R_1 \sim 15–35$ km and $kT_2 \sim 10–20$ keV, $R_2 \sim 2–7$ km [14, 21, 22, 23]). Specifically, the derived 2BB model parameters are in agreement with the results reported previously for intermediate bursts ($kT_1 \sim 4.8$ keV, $R_1 \sim 30$ km and $kT_2 \sim 9.0$ keV, $R_2 \sim 5.7$ km [12, 24]).

The $E_p$ values obtained from the CPL model fits, $E_p \sim 30–37$ keV, are typical of SGR bursts, but there seems to be a difference across SGR sources regarding the power-law indices $\alpha$. Our result on $\alpha$ is comparable to those obtained for SGR 0501+4516 [23] and SGR 1900+14 [11], and is significantly different than the one found for SGR J1550-5418 [14]. Moreover, the measured
spectral parameters are consistent with results obtained using Fermi/GBM observations for much weaker and shorter bursts detected during the SGR 1935+2154 activity in 2015 February.

![Figure 3](image.png)

**Figure 3.** Square of radii of the emitting areas as a function of their temperatures. The soft BB component is shown in red and the hard BB — in blue. Source distance of 10 kpc is assumed. We also plot the $R^2 = kT^{-3}$ relation to guide the eye.

Using the 2BB fits described in Section 2, we calculated the soft and hard BB luminosities for each of the seven burst spectra. Almost all derived luminosities are over $10^{40}$ erg s$^{-1}$, and hence there is just some hint for the saturation effect of the low-$kT$ BB luminosity as it was previously noted for SGR 1900+14 [24]. In order to further investigate this trend, we studied the $R^2$ versus $kT$ distribution (see Figure 3). The sharp edge in the distribution of the data described by the $R^2 = kT^{-3}$ relation indicates the presence of the saturation. So we can use the magnetic Eddington luminosity formula derived in [25]

$$L_{\text{Edd},B} \approx 2 \times 10^{40} \left( \frac{B}{B_{\text{QED}}} \right)^{4/3} \left( \frac{R}{R_{\text{NS}}} \right)^{2/3}$$

where $B_{\text{QED}} \approx 4.4 \times 10^{13}$ G is magnetic field critical value and $R_{\text{NS}}$ is a neutron star radius for which we assume a typical value of 10 km. It can be rewritten in terms of the distance $d$ and peak flux $F_{\text{max}}$ into

$$\left( \frac{d}{\text{kpc}} \right) \approx 0.4 \times \left( \frac{F_{\text{max}}}{\text{10}^{-5} \text{erg cm}^{-2} \text{s}^{-1}} \right)^{-1/2} \left( \frac{kT_{\text{break}}}{\text{keV}} \right)^{5/4} \left( \frac{B_{\text{surf}}}{\text{10}^{14} \text{G}} \right)^{1/4} \left( \frac{R_{\text{NS}}}{10 \text{ km}} \right)^{5/8}$$

Now we can derive an approximate value for the distance by using the saturated flux recorded for the source and the magnetic field strength inferred by timing analysis. For the magnetic field we used a value of $\sim 2.2 \times 10^{14}$ G [26]. $kT_{\text{break}}$ is the energy at which the data in the $R^2$ versus $kT$ distribution start departing from the relation $kT^{-3}$. With the value of $kT_{\text{break}}$ for the studied burst lying in the 12–15 keV range we derive the distance estimate of 7.4–9.8 kpc. However, given that we have seen only one bright intermediate burst from this source, we cannot be sure that the luminosity in the April 12 burst is close to the maximum observable from SGR 1935+2154 and a brighter burst would situate the source closer to us. So, in this work, we estimate the SGR 1935+2154 distance to be $< 10.0$ kpc, in agreement with that of the Galactic supernova remnant G57.2+0.8.
References

[1] Mazets E and Golenetskii S 1981 Ap&SS 75 47–81
[2] Olausen S A and Kaspi V M 2014 ApJS 212 6
[3] Frederiks D D, Golenetskii S V, Palshin V D, Aptekar R L, Ilyinskii V N, Oleinik F P, Mazets E P and Cline T L 2007 Astronomy Letters 33 1–18
[4] Cummmings J, Barthelmy S, Chester M and Page K 2014 ATel #6294
[5] Israel G, Rea N, Zelati F, Esposito P, Burgay M, Mereghetti S, Possenti A and Tiengo A 2014 ATel #6370
[6] Gaensler B 2014 GCN Circular 16533
[7] Pavlović M, Urošević D, Vukotić B, Arbutina B and Göker Ü 2013 ApJS 204 4
[8] Golenetskii S et al. 2015 GCN Circular 17699
[9] Aptekar R et al. 1995 SSRe 71 265–72
[10] Arnaud K 1996 AADASS 101 17
[11] Feroci M, Callandro G, Massaro E, Mereghetti S and Woods P 2004 ApJ 612 408–413
[12] Olive J F, Hurley K, Sakamoto T, Atteia J L, Crew G, Ricker G, Pizzichini G, Barraud C and Kawai N 2004 ApJ 616 1148–58
[13] Lin L et al. 2012 ApJ 756 54
[14] van der Horst A et al. 2012 ApJ 749 112
[15] Israel G L, Belloni T, Stella L, Rephaeli Y, Gruber D E, Casella P, Dall’Osso S, Rea N, Persic M and Rothschild R E 2005 ApJ 628 L53–L56
[16] Strohmayer T E and Watts A L 2005 AAS 37 p 1497
[17] Huppenkothen D et al. 2014 ApJ 787 128
[18] Doneva D D, Gaertig E, Kokkotas K D and Krüger C 2013 Phys. Rev. D 88 044052
[19] Andersson N and Kokkotas K D 1996 Phys. Rev. Lett. 77 4134–37
[20] Israel G L and Stella L 1996 ApJ 468 p 369
[21] Nakagawa Y et al. 2007 OUP 59 653–78
[22] Esposito P et al. 2008 MNRAS 390 L34–L38
[23] Lin L et al. 2011 ApJ 739 87
[24] Israel G et al. 2008 ApJ 685 1114–28
[25] Paczynski B 1992 Acta Astronomica 42(3) 145–53
[26] Israel G L et al. 2016 MNRAS 457 3448–56