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Exceptional flaring activity of the anomalous X-ray pulsar 1E 1547.0-5408

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We studied an exceptional period of activity of the anomalous X-ray pulsar 1E 1547.0-5408 in January 2009, during which about 200 hard X-ray / soft γ-ray bursts were detected by different instruments on board of ESA's γ-ray observatory *INTEGRAL*. Even though the source was outside the *INTEGRAL* instruments field of view during the major part of the outburst, we were able to study the statistical properties as well as spectral and timing characteristics of 84 short (100 ms$-$10 s) bursts from the source. We find that the luminosity of the 22 January 2009 bursts of 1E 1547.0-5408 was $\geq 10^{42}$ erg s^{-1} above $\sim$ 80 keV, which is comparable to that of the bursts of soft gamma repeaters (SGR) and is at least two orders of magnitude larger than the luminosity of the previously reported bursts from AXPs. We identify various morphologies of the bursts. We find that the bursts of 1E 1547.0-5408 harden with increasing luminosity. Such a behavior is opposite of those observed in SGR bursts, but is similar to the hardness-luminosity relation observed in AXP 1E 2259+586. Our observations strengthens the conjecture that AXPs and SGRs are different representatives of one and the same source type.

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1. Introduction

Anomalous X-ray pulsars (AXP) and soft gamma repeaters (SGR) are believed to be young neutron stars with ultra-strong magnetic fields exceeding the Schwinger magnetic field $B_{\rm Schw} = m_e^2 c^3/e\hbar \simeq 4.4\times 10^{13}$ G [26, 21]. SGRs are known to exhibit periods of activity, during which they emit a large amount of short bursts with typical durations of ~ 100 ms and a luminosity reaching $\sim 10^{42}$ erg s^{-1} (see [21] for a recent review). Similar, but much fainter (by several orders of magnitude) bursts are observed also in AXPs [8, 30]. Contrary to the SGR bursts, which exhibit spectral softening with increasing luminosity [11], the brighter AXP bursts appear to have harder spectra [7].

The lightcurves of the AXP bursts have a rich morphology, classified conventionally in two types: short bursts with symmetric time profiles (type A) and longer fast-rise / slow-decay bursts with the decaying tails lasting tens to hundred seconds (type B) [30]. The "type A" bursts resemble the short bursts of SGRs (although with much lower luminosity), while the "type B" bursts are weak analogs of the so-called "giant flares" of SGRs which are usually characterized by a short spike followed by a longer pulsating tail lasting up to thousands of seconds.

1E 1547.0-5408 was discovered by the *Einstein* satellite [18] in the search of an X-ray counterpart of a *COS-B* source and was recently identified as a magnetar in the center of the supernova remnant candidate SNR G327.24-0.13 [9]. A discovery of pulsed radio emission with a period $P \simeq 2$ s and period derivative $\dot{P} \simeq 2.3\times 10^{-11}$ s^{-1} enabled the estimation of the magnetic field close to the neutron star $B \simeq 2.2\times 10^{14}$ G as well as of its distance $D \simeq 9$ kpc [2]. The X-ray flux from the source is known to exhibit large variations in the range of $(0.1-5)\times 10^{-12}$ erg cm^{-2}s^{-1} in the 1-8 keV energy band, which corresponds to variations of the source luminosity 10^{34} erg s^{-1} $\leq L_{\rm X} \leq 10^{35}$ erg s^{-1} [14].

In this paper we report on a study of the episode of bursting activity of 1E 1547.0-5408 in January 2009. During this episode, about 200 bursts from the source [24, 23] were detected by the Anti-Coincidence Shield (ACS) of the spectrometer SPI on board the *INTEGRAL* satellite [29]. The flaring activity of the source was initially discovered by *Swift* [13] and was also observed by the *Fermi/GBM* telescope [4, 28]. Major episodes of activity consisting of clusters of $\sim 10-10^2$ bursts are typical for SGRs, but in the case of AXPs such activity was detected only once, in the source 1E 2259+586 in 2003 [7]. The extended report of our study is presented in the paper [25].

2. Data analysis

The ACS is an active shield of the INTEGRAL spectrometer SPI [27]. It features huge, nearly isotropic effective area (about 1 m^2). Overall detector count rate is recorded in time intervals of 50 ms. No energy or directional information is available. The low-energy threshold corresponds to approximately 80 keV. The ISGRI detector is part of the IBIS telescope on-board of *INTEGRAL*. It is sensitive to photons between 15 keV and 1 MeV. ISGRI works in photon-by-photon mode allowing to produce the high time resolution lightcurves. The walls of the collimator above the ISGRI detector are made of lead and act as a shield to photons with energies of up to 200 keV.

For our analysis we have extracted the ACS and ISGRI detector lightcurves from the data of *INTEGRAL* revolution 766, which covers a period from 2009-01-20T14:34 to 2009-01-23T04:23

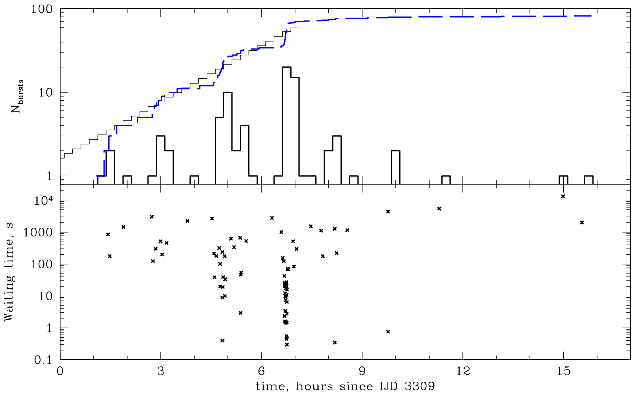

Figure 1: *Top*: the thick solid line is the rate of bursts as a function of time on 22 January 2009. The dashed blue histogram shows the cumulative burst distribution. The thin straight solid historgam shows a fit with an exponentially rising burst rate with rise time $T_r = 1.94$ hr. *Bottom*: the waiting time between subsequent bursts as a function of time.

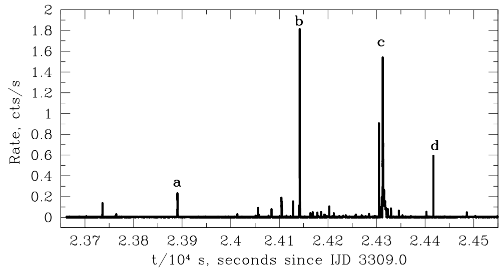

Figure 2: SPI/ACS lightcurve during the main activity episode of 1E 1547.0-5408 between 6:30 and 7:00, 22 January 2009 (UTC).

UTC. During this revolution 1E 1547.0-5408 was at $\sim 60^\circ$ off-axis angle, outside the field of view (FoV). Using the `ii_light` (from the OSA 7.0 [5]) tool we have extracted ISGRI detector lightcurves in two energy bands, $20-60$ keV and $60-200$ keV and have applied the barycentric time correction.

We have identified the moments of the on-set of individul bursts as the moments when the count rate in the ACS rises above the 5σ level above the background, defined as 10-second coutrate average. To get rid of the instrumental short spikes observed in the ACS (most likely related to particle precipitations) we accepted for the statistical studies only the ACS bursts with the couterparts in ISGRI detector lightcurves with a significance higher than 3 sigma. This selects 84 out of about 200 bursts detected in the ACS lightcurve during the analyzed period.

3. Results

3.1 The 22 January 2009 activity episode

The upper panel of the Figure 1 shows the evolution of the rate of bursts on 22 January 2009. The maximum of burst activity happened around UTC 22-01-09T06:40 with more than 40 bursts detected within half-an-hour. This major activity episode was preceded by several weaker episodes, with a growing peak burst rate. A fit of the evolution of the burst rate with an exponential function, $N \propto \exp\left[(t-t_{\max})/T_r\right]$, gives the rise time $T_r = 1.94 \pm 0.14$ hr. (see upper panel of Fig. 1). The increase of the burst rate ended abruptly half an hour after the major activity episode and subsequently continued to decrease on several hour- and day-time scales.

3.2 Individual burst lightcurves

An expanded view of the strongest bursts, marked **a**, **b**, **c** and **d** in Fig. 2 is shown in Fig. 3. The upper panels of the figure show the evolution of the SPI/ACS ($R_{\rm ACS}$, measured in cts s^{-1}, dashed blue curve) and ISGRI 20-60 keV (R_{20-60}, measured in cts cm^{-2}s^{-1}, solid red curve) and 60-200 keV (R_{60-200}, measured in cts cm^{-2}s^{-1}, dotted black curve) count rates. The middle panel shows the evolution of the ISGRI-ISGRI hardness ratio $H_1 = R_{60-200}/R_{20-60}$, while the lower panels show the evolution of the ACS-ISGRI hardness ratio, defined as $H = 10^{-6}R_{\rm ACS}/R_{20-60}$. All the four strongest bursts which happened during the main activity episode have qualitatively different time profiles.

The lightcurve of burst **a** has a "flat top" shape with a sharp rise and decay and a nearly constant flux "plateau" period of ~ 1 s duration. This shape is similar to the one of the "precursor" to the bright flare of the SGR 1806-20 reported by [15]. During the "plateau" phase the spectrum of the source does not vary, as one can see from the lower panel of Fig. 3a.

The strongest burst shown in Fig. 3b consists of a bright short spike of ~ 100 ms duration, and a ~ 1 s long softer "tail". The peak count rate in the ACS detector is $\sim 1.8\times 10^6$ cts s^{-1} and close to the one observed in the giant flare of SGR 1820-06 by [20]. However, in both cases the ACS signal was affected by saturation effects. An order-of-magnitude conservative estimate of the peak flux could be obtained assuming all the photons to have the energy just above the threshold of the detectors ($E_{\rm thr} \simeq 80$ keV) and adopting the minimal value of the ACS effective area ($A_{\rm eff,ACS}(0.2\ {\rm MeV}) \sim 10^3$ cm^2 [27]. One then finds the limit on the flux [1] $F \geq \frac{E_\gamma R_{\rm ACS}}{A_{\rm eff,ACS}} \simeq 3\times 10^{-4}$erg cm^{-2}s^{-1} and the luminosity $L_{\mathbf{b}} = 4\pi D^2 F \geq 3\times 10^{42}$erg s^{-1}. This luminosity is several orders of magnitude larger than that of the bursts of the AXPs observed up to now, but comparable to the one of a typical SGR burst (see e.g. [21]). The 100 ms burst phase of the brightest event is followed by a softer "afterglow" tail which is characterized by a power-law decay profile with $T_{\rm dec} \simeq 10$ ms for the ACS and ISGRI 60-200 keV energy band and $T_{\rm dec} \simeq 30$ ms in the ISGRI 20-60 keV energy band. The powerlaw decay ends abruptly ~ 1 s after the start of the burst.

A somewhat weaker burst shown in Fig. 3c exhibits a spike plus afterglow morphology similar to the one of burst **b**, but with a much larger fraction of the power emitted during the afterglow phase. The hardness ratio does not change over the time interval where ISGRI data are available. One can clearly identify the oscillations with the period $\simeq 2$ s, close to the period of rotation of the neutron star. These oscillations were previously reported by [22].

The burst **d** shown in the Fig. 3d consists of a single hard spike of the duration of ~ 100 ms, with almost no detectable afterglow. The ratio of the peak luminosity of the spike to the peak luminosity of the afterglow in this burst and the hardness of the spike emission are comparable to the one of the strongest burst **b**.

3.3 Statistical study of the burst properties

We found significant correlation between the hardness and the ACS countrate. While the value of the hardness of the brightest bursts is affected by the saturation effects, for the moderate flux values the observed conclusion is robust. The dependence of the hardness of the spectrum on the luminosity was noticed in the bursts of 1E 2259+586 by [7]. This type of dependence is the opposite of those observed in SGR bursts, for which a softening of the spectrum with increasing luminosity was observed [11].

[1]the analysis of [23], which appeared after this paper was submitted, results in a comparable estimate of the lower limit on the source flux.

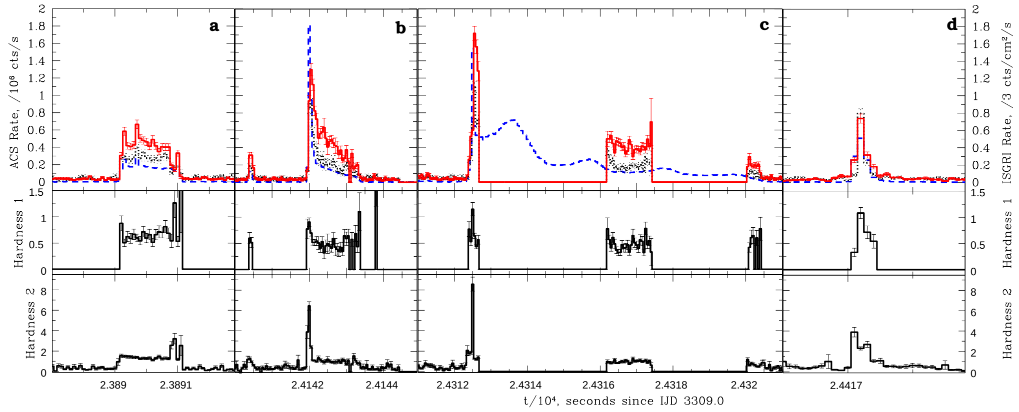

Figure 3: The lightcurves of the bursts marked as **a,b,c** and **d** in Fig.2. See the explanations in the text.

In most of the bursts a significant contribution to the total energy output comes from the afterglow emission. At the same time the burst duration T is correlated with the peak flux, i.e. bursts with stronger spikes possess on average stronger afterglows. The observed fluence-duration correlation ($T_{\mathrm{peak}}^{1.4\pm0.2}$ and $F \sim T^{1.58\pm0.08}$) is different from the one observed in 1E 2259+586 ($F \sim T^{0.54\pm0.08}$ by [7]) and instead resembles more the fluence-duration relation of SGR bursts, e.g. $F \sim T^{1.13}$ in SGR 1900+14, [10].

The distribution of burst durations can be fit with a log-normal distribution with a mean of $T = 68 \pm 3$ ms and a scatter of 30 ms$< T <$ 155 ms.

Figure 4 shows a comparison of the shifted by an integer number of periods afterglows of three bright bursts: the solid line - **b**, the dashed line - **c** and the dotted line - a somewhat weaker burst which happened two hours later. Although the phases of the maxima of the pulsed afterglow do not coincide exactly, they are rather close to each other. This might indicate that the afterglows of different bursts are produced by one and the same "hot spot" on the neutron star's surface or that the "trapped fireball" in the neutron star's magnetosphere always appears at the same latitude / longitude.

Contrary to the pulsed afterglows, the short spikes of different bursts do not arrive in phase. For example, the burst shown by the green dotted line in Fig. 4 has a sharp start of the afterglow, but does not possess an initial spike at all. We have also found bursts in which the moment of arrival of the short spike is delayed compared to the moment of the onset of the "afterglow-like" emission.

The large effective area of the ACS detector enables us to detect the bursts with a fluence down to three orders of magnitude lower than the one of the brightest bursts. The fluence distribution follows a power law with an exponent -0.5 ± 0.1 over a dynamic range of ~ 3 decades in fluence. This behavior is similar to the one observed in the SGR bursts [10]. The luminosities of the brightest bursts from 1E 1547.0-5408 are $\geq 10^{42}$ erg s^{-1} while of the weakest one - $\sim 10^{39}$ erg s^{-1}, matching the luminosity of the brightest burst from AXPs detected before. Interestingly, inspite of significant differences in the luminosity, the bursts of the 1E 2259+586 [7] featured similar power-law-shaped distributions (with the slope of 0.7 ± 0.1). The distribution of the burst peak count rates has a smaller dynamical range. A powerlaw fit of this distribution, is characterized by a slope of -0.8 ± 0.2, flatter than that of the distribution of the burst fluxes in 1E 2259+586, 1.42 ± 0.13.

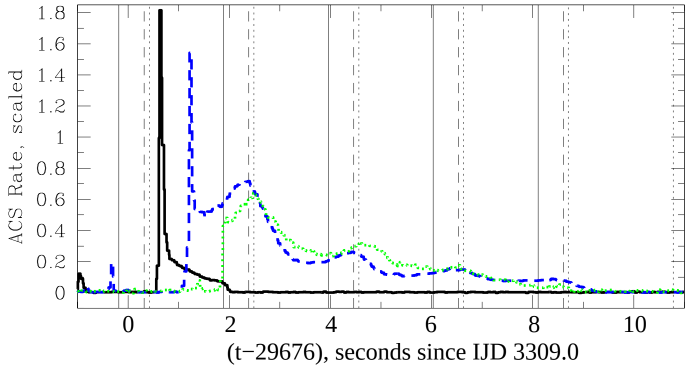

Figure 4: Relative phases of the pulses of the burst afterglows. The green dotted line shows a burst which occurred on January 22, 8:18 am. Black solid line shows the brightest burst **b** shifted by 2671 periods forward in time. The blue dashed line shows the second-brightest burst **c** shifted by 2589 periods. The count rate of this burst is multiplied by a factor of three to highlight the similarity with the time profile of the burst **c**. The vertical dotted and dashed lines show the phases of the maxima of the pulses of the burst afterglows. The vertical solid lines are shifted by $\Delta\phi = 0.25$ with respect to the vertical dotted lines

4. Discussion and conclusions

We have studied an exceptional period of activity of 1E 1547.0-5408 which occurred on 22 January 2009. During this activity period, about 200 bursts were detected by SPI/ACS and 84 of them were also detected by IBIS/ISGRI detector. The luminosity of the brightest of these bursts is substantially brighter than ever detected from an AXP and comparable to the luminosity of the SGR bursts. In spite of the fact that the source was outside of the field of view of the *INTEGRAL* instruments, we were able to study spectral and temporal characteristics of the bursts, which appeared to be strong enough to penetrate through the walls of the IBIS imager.

We have found that the activity of the source has exponentially increased on the time scale of about one hour, reaching a peak at around UTC 2009-22-01T06:40. The maximum of the activity was characterized by a very high rate of bursts from the source, with the minimum of the waiting time between subsequent bursts reaching 0.2 s. We estimate the lower limit on the peak luminosity of the brightest burst to be $L > 3\times 10^{42}$ erg s^{-1}. Our study of the statistical properties of the large amount of the 1E 1547.0-5408 bursts reveals that the typical duration of the bursts is ~ 100 ms. The distribution of the burst duration extends to ~ 10 s. We find that brighter bursts are characterized by longer durations and by harder spectra. The extended afterglows of the brightest bursts exhibit pulsations with a period equal to the rotation period of the neutron star. The phases of the maxima of the pulsed afterglow emission of different bursts are close to each other but the bright short spikes of different bursts do not tend to arrive at a preferred phase.

A consistent interpretation of the burst timing and spectral properties observed in the 22 January 2009 activity episode of 1E 1547.0-5408 within the two main models of the magnetar flares, the "crustal fracture" and the "magnetic reconnection" models [26, 19], requires further theoretical investigation. Observation of SGR-like bursts from an AXP adds additional argument in favor of the hypothesis that AXPs and SGRs form a unique source population, so that 1E 1547.0-5408 is an "intermediate" AXP/SGR representative of this population.

References

[1] Burgay N., Israel G. L., Possenti A. et al., 2009, ATEL 1913.

[2] Camilo F., Ransom S.M., Halpern J.P., Reynolds J., 2007, Ap.J., 666, L93.

[3] Camilo F., Halpern J.P., Ransom S.M., 2009, ATEL 1907.

[4] Connaughton V., Briggs M., 2009, GCN 8835.

[5] Courvoisier T.J.-L., Walter, R., Beckmann V. et al., 2003, A& A, 411, L53.

[6] den Hartog P.R., Kuiper L., Hermsen W., 2009, ATEL 1922.

[7] Gavriil F.P., Kaspi V.M., Woods P.M., 2004, Ap.J., 607, 959.

[8] Gavriil F.P., Kaspi V.M., Woods P.M., 2002, Nature, 419, 142.

[9] Gelfand J.D., Gaensler B.M., 2007, Ap.J., 667, 1111.

[10] Gögüş E., Woods P.M., Kouveliotou C., van Paradijs J., Briggs M.S., Duncan R.C., Thompson C., 1999, Ap.J., 526, L93.

[11] Gögüş E., Kouveliotou C., Woods P.M., Thompson C., Duncan R.C., Briggs M.S., 2001, Ap.J. 558, 228.

[12] Golenetskii S., Aptekar R., Mazets E. et al., 2009, GCN 8913.

[13] Gronwall C., Holland S. T., Markwardt C. B. et al., 2009, GCN 8833.

[14] Halpern J.P., Gotthelf E.V., Reynolds J., Ransom S.M., Camilo F., 2008, Ap.J., 676, 1178.

[15] Hurley K., Boggs S. E., Smith D. M. et al., 2005, Nature, 434, 1098. T. E., Woods P. M., Kouveliotou C., Thompson C., Duncan R. C., Dieters S., Swank J. H., van Paradijs J., Finger M., Ap.J, 558, 237

[16] Kouveliotou C., von Kienlin A., Fishman G. et al., 2009, GCN 8915.

[17] Kuiper L., den Hartog P.R., Hermsen W., 2009, ATEL 1921.

[18] Lamb R.C., Markert T.H., 1981, Ap.J., 244, 94.

[19] Lyutikov M., 2002, Ap.J., 580, L65.

[20] Mereghetti S., Götz D., von Kienlin A., Rau A., Lichti G., Weidenspointner G., Jean P., 2005, Ap.J., 624, L105.

[21] Mereghetti S., 2008, Astron. Astrophys. Rev., 15, 225.

[22] Mereghetti S., Gotz D., von Kienlin A. et al., 2009, GCN 8841.

[23] Mereghetti S., Götz D., Weidenspointner G. et al., 2009a, Ap.J., 696, L74.

[24] Savchenko V., Beckmann V., Neronov, A. et al., 2009, GCN 8837.

[25] Savchenko V., Neronov A., Beckmann V., Produit N., Walter R., 2009, A& A, 510, L77

[26] Thompson C., Duncan R.C., 1995, MNRAS, 275, 255.

[27] von Kienlin A., Beckmann V., Rau A., et al., 2003, A& A, 411, L299.

[28] von Kienlin A., Connaughton V., 2009, GCN 8838.

[29] Winkler, C., Courvoisier T. J.-L.; Di Cocco G., et al. 2003, A&A, 411, L1.

[30] Woods P.M., Kouveliotou C., Gavriil F.P. et al., 2005, Ap.J., 629, 985.