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Magnetar-like Emission from the Young Pulsar in Kes 75

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We report detection of magnetar-like X-ray bursts from the young pulsar PSR J1846−0258, at the center of the supernova remnant Kes 75. This pulsar, long thought to be rotation-powered, has an inferred surface dipolar magnetic field of 4.9×10^{13} G, higher than those of the vast majority of rotation-powered pulsars, but lower than those of the ∼12 previously identified magnetars. The bursts were accompanied by a sudden flux increase and an unprecedented change in timing behavior. These phenomena lower the magnetic and rotational thresholds associated with magnetar-like behavior, and suggest that in neutron stars there exists a continuum of magnetic activity that increases with inferred magnetic field strength.

Magnetars are young, isolated neutron stars having ultra-high magnetic fields (*2, 3*). Observational manifestations of these exotic objects include the Soft Gamma Repeaters (SGRs)

and the Anomalous X-ray Pulsars (AXPs). Magnetars exhibit a variety of forms of radiative variability unique to their source class; these include short (<1 s) X-ray and gamma-ray bursts, and sudden flux enhancements that decay on time scales of weeks to months, both of which are too bright to be powered by rotational energy loss (*4*). A major puzzle in neutron star physics has been what distinguishes magnetars from neutron stars that have comparably high fields, yet no apparent magnetar-like emission (*5*).

The 326-ms PSR J1846−0258 is the central isolated neutron star associated with the young shell-type supernova remnant (SNR) Kes 75 (SNR G29.6+0.1; see ref 1 for details). Assuming standard magnetic dipole braking, this pulsar has among the largest dipolar magnetic fields of the known young rotation-powered pulsars and the sixth largest overall, $B \equiv 3.2\times10^{19}$ G $\sqrt{P\dot{P}} = 4.9\times10^{13}$ G, where P is in seconds. In addition, its spin-down age of $\tau \equiv P/(n-1)\dot{P} = 884$ yr is the smallest of all known pulsars (*1, 6*). The observed X-ray luminosity of PSR J1846−0258 is $L = 4.1\times10^{34}\,(d/6\,\mathrm{kpc})^2$ erg s^{-1} in the 3−10 keV band, assuming a distance of $d \sim 6$ kpc, the mean distance found from HI and ^{13}CO spectral measurements (*8*). The pulsar has all the hallmarks of being rotation-powered – a radiative output well under its spin-down luminosity ($\dot{E} \equiv 3.9\times10^{46}\dot{P}/P^3\,\mathrm{erg\,s^{-1}} = 8.1\times10^{36}$ erg s^{-1}), an otherwise unremarkable braking index ($n = 2.65$) (*6*), and a bright pulsar wind nebula (see Fig. 1). This pulsar is one of only ∼3 young rotation-powered pulsars for which no radio emission is detected, although this may be due to beaming.

Observations in the direction of Kes 75 obtained with the *Rossi X-ray Timing Explorer* (*RXTE*) have revealed several short bursts of cosmic origin lasting ∼0.1 s (see Fig. 2). We discovered four bursts in a 3.4 ks observation made on 2006 May 31 and a 5th in a 3.5 ks observation made on 2006 July 27.

These data were obtained with the Proportional Counter Array (PCA) onboard *RXTE* which provides ∼μs time resolution and 256 spectral channels over the ∼2−60 keV bandpass, and

consists of 5 independent sub-units (PCUs). The bursts are plotted in Fig. 2 and their properties are listed in Table 1. We quantified the burst properties as we have for those seen in bursting AXPs (see supporting online text 9, 10, 11, 12). All five bursts were highly significant, and were recorded in all operational PCUs simultaneously. We found no additional bursts in the 21.4 Msec of available data of this field collected by *RXTE* over the past 7 years.

Because of the PCA's large ($1^\circ \times 1^\circ$) field-of-view, the origin of the bursts was not immediately apparent. However, we could unambiguously identify PSR J1846−0258 as their origin because the bursts coincided with a dramatic rise in its pulsed flux, which lasted ∼2 months (see Fig. 2) and was remarkably similar to those observed from AXPs (*13, 14, 15*). The pulsed flux was extracted according to the method detailed in ref 16 and corrected for collimator response and exposure for each PCU. We model the recovery from the pulsed flux enhancement as an exponential decay (with $1/e$ time constant 55.5±5.7 day) and estimate a total 2−60 keV energy release of 3.8−4.8$\times 10^{41}\,(d/6\,\mathrm{kpc})^2$ erg, assuming isotropic emission. If we assume a power-law model for the flux decay, commonly used for the magnetars, we obtain an index of −0.63±0.06. However, this model is rejected with $\chi^2_\nu(51\ \mathrm{DoF}) = 1.31$ compared with $\chi^2_\nu(51\ \mathrm{DoF}) = 0.95$ for the exponential model.

At the onset of the outburst, the timing noise of the source changed dramatically from that typical of a young rotation-powered pulsar to that typical of AXPs. PSR J1846−0258 was spinning down smoothly with a braking index of n =2.65±0.01 (*6*) until phase coherence was lost on MJD 53886, the same observation in which the first four bursts were observed. This loss of phase coherence could signal a spin-up glitch as has been seen to accompany other AXP radiative events (*13, 17, 18*). The dramatic sudden timing noise makes the determination of accurate glitch parameters via phase-coherent timing difficult. In the most recent data, the timing noise appears to have settled somewhat, though has not relaxed to its pre-burst behavior.

We also examined archival high-resolution CCD images of Kes 75 obtained with the *Chan-*

dra X-ray Observatory (*CXO*) both before (2000 Oct) and very fortuitously during (2006 June) the event. This allows us to identify the dramatic change in the flux of the pulsar relative to its bright, but relatively constant, pulsar wind nebula (see Fig. 1 and supporting online text).

The *CXO*-measured spectrum at the outburst epoch softened significantly relative to quiescence. A fit to a power-law model in 2006 produced a larger value for the photon index, with Γ=1.89$^{+0.04}_{-0.06}$ and 1.17$^{+0.15}_{-0.12}$ for epochs 2006 and 2000, respectively (3-σ errors). Interestingly, the larger value of the photon index is now closer to those seen in magnetars ($\Gamma\sim2-4$). Due to this softening, the 0.5–2 keV flux showed the largest increase, a factor of 17^{+11}_{-6}, while the $2-10$ keV flux increased by a factor of $5.5^{+4.5}_{-2.7}$ (3-σ errors, see Fig. 1). Though the 2006 spectrum is softer, the large absorption precludes the identification of any significant thermal components. Note that the *CXO* spectral analysis was non-trivial due to the brightness of the source and associated CCD pile-up; see online supporting text for details.

The coincidence of the bursts with the flux enhancement (see Fig. 2), the distinct changes in the pulsar spectral properties (see Fig. 1), and the timing anomaly and sudden change in timing noise properties all firmly establish PSR J1846$-$0258 as the origin of the bursts.

This is the first detection of X-ray bursts from an apparent rotation-powered pulsar. It is instructive to compare the burst properties with those of SGRs and AXPs. SGRs are characterized by their frequent, hyper-Eddington ($\sim10^{41}$ erg s^{-1}), and short ($\sim$0.1 s) repeat X-ray bursts. AXPs also emit such bursts, albeit less frequently (*9*). The bursts from PSR J1846$-$0258 were short ($<$0.1 s), showed no emission lines in their spectra, and occurred preferentially at pulse maximum. The peak luminosities (L_p) of all bursts were greater than the Eddington luminosity (L_E) for a 1.4 $M_\odot$ neutron star, assuming isotropic emission and a distance of $d = 6$ kpc (*8*) (burst 2 had $L_p > 10L_E$). Considering the distribution of SGR and AXP burst temporal, energetic and spectral properties (*20, 10*), the Kes 75 bursts are indistinguishable from many of the bursts seen in AXPs and SGRs.

PSR J1846−0258's pulsed flux flare is also a magnetar hallmark. A twisted magnetosphere and associated magnetospheric currents induce enhanced surface thermal X-ray emission, and resonant upscattering thereof (*21,22*). Flux enhancements and their subsequent decay in AXPs have been interpreted as sudden releases of energy (either above or below the crust) followed by thermal afterglow, in which case there is an abrupt rise with a gradual decay. A power-law fit was an excellent characterization of AXP 1E 2259+586's flux decay after its 2002 outburst. For PSR J1846−0258, such a model did not fit the data as well as an exponential (see Fig. 2). Spectral changes are also expected with these enhancements. The softening of the source's spectrum suggests that it underwent a transition from a purely magnetospheric-type spectrum, typical of energetic rotation-powered pulsars, to one consistent with the persistent emission from magnetars. For this reason, it is difficult to directly compare the spectral characteristics of this flux enhancement to those of other magnetars in outburst. The total 2−10 keV energy released during the flux enhancement ($3.3-3.8\times10^{41}\,(d/6\,\mathrm{kpc})^2$ erg, assuming isotropic emission) is comparable that released in the 2007 flux enhancement (*18*) of AXP 1E 1048.1−5937 ($\sim5\times10^{42}\,(d/9\,\mathrm{kpc})^2$ erg), the most most energetic enhancement yet seen from this AXP. It is also comparable to the energy released during the rapid ($\sim3\times10^{39}\,(d/3\,\mathrm{kpc})^2$ erg) and gradual ($\sim2\times10^{41}\,(d/3\,\mathrm{kpc})^2$ erg) decay components of the 2002 outburst of AXP 1E 2259+586 (*16*). Similar to AXP 1E 2259+586's 2002 outburst (*16*), the energy released by PSR J1846−0258 during the observed short bursts represents only a small (∼0.03%) fraction of the total outburst energy.

Prior to showing magnetar-like emission, PSR J1846−0258 exhibited timing noise and a glitch in 2001 (*6*) that were both similar to what has been seen observed in other comparably aged (i.e. $\tau\simeq1$ kyr) rotation-powered pulsars. By contrast, in 2007, PSR J1846−0258 exhibited much larger timing noise, such that the root mean square phase residual after subtracting a model including the spin frequency, and its first and second derivative is a factor of ∼33 larger

than before, for the same duration of observations. Such a dramatic, sudden change in timing noise characteristics has never been seen before in a rotation-powered pulsar. The coincidence of the enhanced timing noise with the flux flare is also reminiscent of behavior exhibited by AXP 1E 1048.1−5937 (*15*).

Our discovery of distinctly magnetar-like behavior from what previously seemed like a *bona fide* rotation-powered pulsar may shed new light on the magnetic evolution of these objects, and whether their extreme fields originate from a dynamo operating in a rapidly rotating progenitor (*23*), magnetic flux conservation (*24*), or a strongly magnetized core, initially with crustal shielding currents (*25*). In the first two scenarios, magnetars are born with high magnetic fields which subsequently decay. In the third recently proposed scenario, the very large magnetic fields of magnetars slowly emerge as the shielding currents decay (*25*). This source has a well measured braking index ($n = 2.65 \pm 0.01$) (*6*), at least before outburst, which is significantly less than 3, suggesting that its spin properties, and hence magnetic field are headed towards the magnetar regime (*26*). In this case, the timescale for magnetic field decay, given by the magnetic field divided by its decay rate will be $B/(\partial B/\partial t)$∼8 kyr, at which point PSR J1846−0258 will have P ∼1.3 s. However, other mechanisms, such as the interaction between a strong relativistic pulsar wind nebula (PWN) and the magnetosphere (*27*), can also yield the value of n measured for PSR J1846−0258. In this case, the magnetar-like behavior could be a result of the moderately high B, with no B evolution occurring.

There have been suggestions of magnetar-related emission from other high-magnetic-field radio pulsars, e.g. PSR J1119−6127 (*28*), but, until now, nothing that could not also be explained within the constraints of rotation-powered pulsar physics. It has been suggested (see ref 5) that the high-B field pulsars are related to transient AXPs, magnetars generally in quiescence whose X-ray emission can grow by factors of ∼hundreds in outburst. Interestingly, the first two reports of radio pulsations from a magnetar were from transient AXPs after out-

burst (*29, 30*). Despite a lack of radio emission, the behavior of PSR J1846−0258 reinforces the connection between transient AXPs and high-B rotation-powered pulsars, and suggests that careful monitoring of other high-B rotation-powered pulsars (*5*) is warranted.

The addition of PSR J1846−0258 to the list of sources which emit magnetar-like events provides insight into the origin of this activity. Extreme magnetic activity is prevalent in the SGRs which exhibit giant flares with energy releases upwards of 10^{44} ergs (see ref 31 for an example) and are also prolific busters, emitting bursts fairly frequently, typically multiple times per year, with larger outbursts occurring every few years. AXPs can be considered milder versions of SGRs, with several showing sporadic short SGR-like events, though more rarely than in SGRs, with even modest outbursts occurring only once or twice per decade. Now, Kes 75, weakly magnetized by magnetar standards, shows properties of both rotation powered pulsars and AXPs, and seems to produce an outburst only roughly every decade. The detection of magnetar-like emission from Kes 75 suggests that there is a continuum of "magnetar-like" activity throughout all neutron stars which depends on spin-inferred magnetic field strength.

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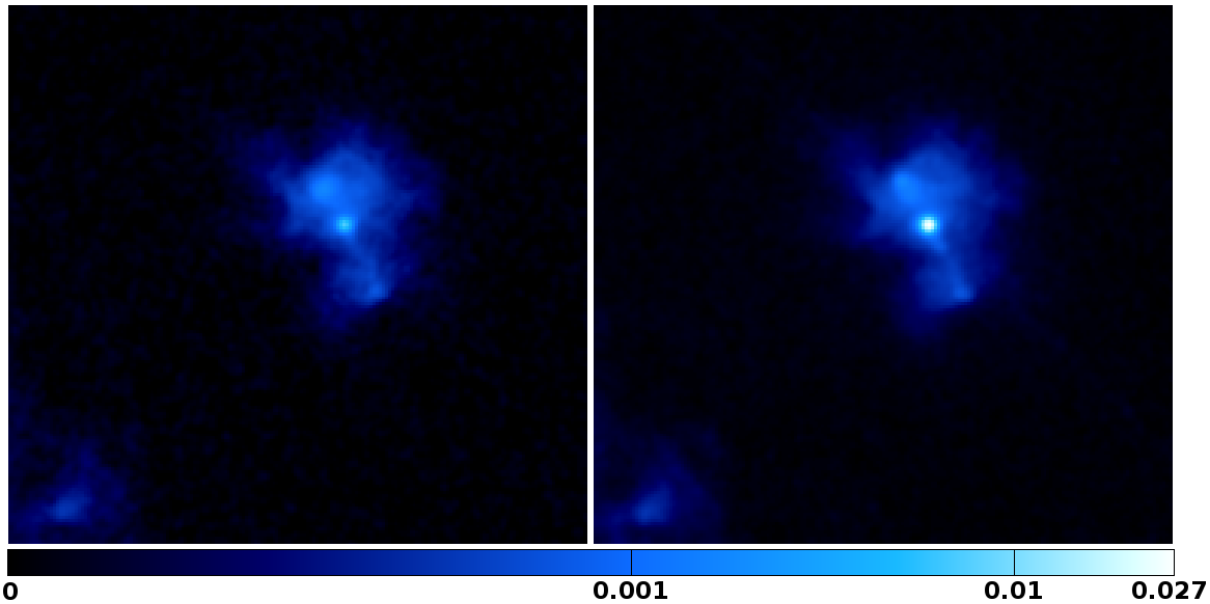
0
0.001
0.01
0.027

Fig. 1. High resolution *Chandra* X-ray images (0.5−10 keV) of PSR J1846−0258 in SNR Kes 75 centered on the pulsar and its surrounding PWN, obtained before and during the 2006 outburst. Following the bursts, the pulsar became brighter as well as softer. These images were made using archival ACIS-S3 observations obtained on 2000 Oct 15-16 (*left*) and very fortuitously 2006 June 5, 7-8, 9, 12-13 (*right*) and are background-subtracted, exposure-corrected, smoothed with a constant Gaussian with width σ=0.5″ and finally displayed using the same brightness scale.

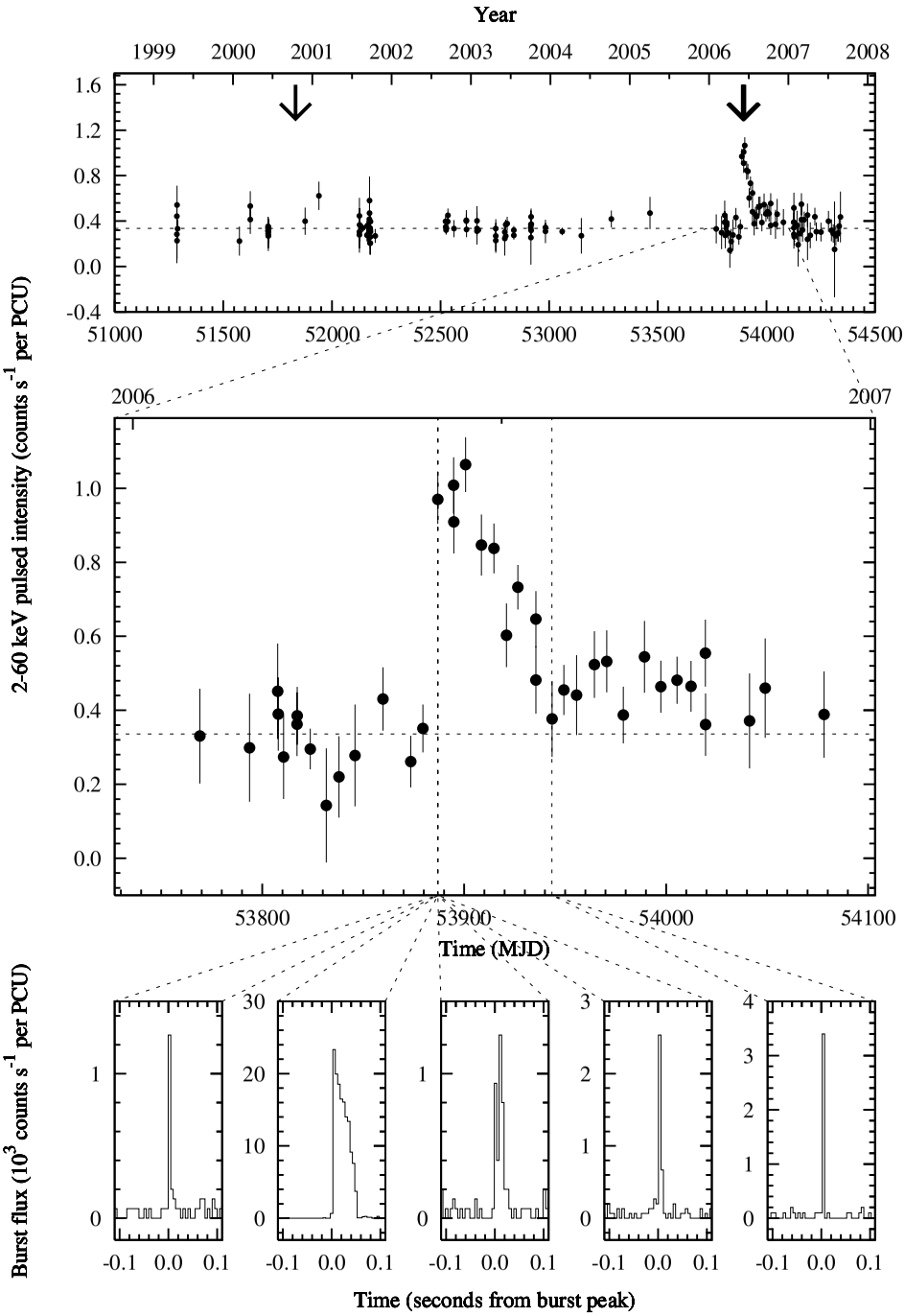
Year
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2-60 keV pulsed intensity (counts s-1 per PCU)
Time (MJD)
Burst flux (10^3 counts s-1 per PCU)
Time (seconds from burst peak)

Fig. 2. Top: Pulsed flux history of PSR J1846−0258 showing the prominent outburst of June 2006 as recorded in the 2−60 keV band by *RXTE*. The horizontal dotted line represents the persistent flux level. Epochs corresponding to *CXO* observations are indicated with arrows. Middle: The light curve around the outburst. The vertical dashed lines indicate the epochs of the observations containing the bursts, 2006 May 31 (4 bursts) and 2006 July 27 (1 burst). The leftmost vertical dashed line also coincides with the time when phase coherence was first lost. Bottom: The 2−60 keV *RXTE* X-ray lightcurves corresponding to five bursts detected from PSR J1846−0258, sampled with 5 ms bins. The bursts lasted for ∼0.1 s and were detected with high significance from two data sets obtained on 2006 May 31 and 2006 July 27. Notice that in 7 years of *RXTE* observations the only bursts found either occur at the onset of the ∼2 month X-ray outburst (4 bursts) or at the end of the decay (1 burst).

Table 1	PSR J1846−0258 Burst Temporal and Spectral Properties				
	Burst 1	Burst 2	Burst 3	Burst 4	Burst 5
Temporal properties					
Burst day (MJD)	53886	53886	53886	53886	53943
Burst start time (fraction of day)	0.92113966(5)	0.93247134(1)	0.93908845(2)	0.94248467(5)	0.45543551(1)
Rise time, t_r (ms)	$4.2^{+3.5}_{-2.0}$	$1.1^{+0.9}_{-0.5}$	$1.90^{+1.7}_{-0.9}$	$4.1^{+3.1}_{-1.9}$	$0.9^{+2.2}_{-0.7}$
T_{90} (ms)	$71.8^{+38.0}_{-5.5}$	$42.9^{+0.3}_{-0.2}$	$137.0^{+11.4}_{-36.2}$	$33.4^{+29.1}_{-23.1}$	$65.3^{+0.7}_{-0.5}$
Phase (cycles)	-0.49(1)	-0.04(1)	-0.20(1)	-0.05(1)	-0.08(1)
Fluences and fluxes					
T_{90} Fluence (counts/PCU)	8.9±0.7	712.8±2.5	18.3±0.7	18.4±0.7	18.4±1.1
T_{90} Fluence (10^{-10} erg/cm^2)	4.1±2.4	289.9±13.1	6.6±2.5	5.8±1.7	5.3±2.0
Flux for 64 ms (10^{-10} erg/s/cm^2)	57±36	4533±227	99±41	97±31	79±32
Flux for t_r (10^{-10} erg/s/cm^2)	678±427	5783±885	810±385	828±284	2698±1193
Spectral properties					
Power-law index	0.89±0.58	1.05±.04	1.14±0.34	1.36±0.25	1.41±0.31
χ^2/DoF (DoF)	0.42 (1)	1.16 (55)	0.97 (3)	0.35 (2)	1.18 (2)

Table 1. All the quoted errors represent 1-σ uncertainties unless otherwise indicated. All times are given in units of UTC corrected to the Solar System barycenter using the source position R.A.=$18^{\rm h}46^{\rm m}24\overset{\rm s}{.}94$, decl=$-02^\circ58'30\overset{''}{.}1$ and the JPL DE200 ephemeris (*7*).

Supporting Online Text

Burst Properties. We defined the burst peak time as the midpoint between the two events having the shortest separation in the peak bin of the 31.25-ms digitized $2-60$ keV PCA lightcurve. The error on the burst peak is determined using the rise time (t_r) method outline in ref 10. The burst background rates were measured by averaging the adjacent 0.5-s flux. We used a sliding 64 ms boxcar on an event-by-event level to determine peak flux. The total burst fluence is calculated by integrating the events within a 0.1 s interval centered on the burst peak and subtracting the modeled background component. T_{90} is defined as the time between when the burst fluence goes from 5% to 95% of its total fluence. Burst spectra were extracted from a 1.2 s interval in the lightcurve centered on the peak emission as defined above. The background is estimated from the same adjacent interval as used for the burst fluence and flux analysis. Spectra were grouped for a minimum of 15 counts per bin after background subtraction and fitted with a absorbed power-law model in the $2-60$ keV energy range using `XSPEC`. The column density was held fixed at N_H=4$\times$10^{22} cm^{-2}, the value found by ref 7 and ref 32. Response matrices were generated using the standard software. This provided a good fit for burst 2 which had the most counts, significantly better then for an absorbed blackbody model. The statistics for the other bursts were too poor to distinguish models. To calibrate the burst fluxes and fluences we calculated a factor from the $2-60$ keV count rate to power-law flux (unabsorbed) in the same band using the burst's power-law index (see Table 1), and multiplied our total fluence and peak fluxes by this factor.

Imaging Observations of PSR J1846$-$0258. The data were processed using the CIAO v3.3 and CALDB v3.2.2 software and subjected to the standard processing, resulting in effective exposure times of $\sim$37 ks and $\sim$154 ks for the 2000 and 2006 observations, respectively. For the spectral analysis, great care is needed as these two observation are strongly effected by CCD

"pile-up" (*33,34*), where two or more photons are recorded in a single CCD pixel, thus distorting the overall spectrum. Each observation is uniquely effected because it depends on count rate and the CCD read-out times (3.2 s and 1.8 s for the 2000 and 2006 observations, respectively). The background-subtracted count rate for the first epoch was 0.092 ± 0.002 cts s^{-1} in the 1–10 keV range with a pile-up fraction of $6 \pm 4\%$. Despite a faster read-out time for the 2006 observation, the pile-up fraction increased to $25 \pm 3\%$ for the 2006 observations due to the higher pulsar flux of 0.330 ± 0.005 cts s^{-1}. To take into account pile-up in our spectral analysis, we followed the prescription of ref 33. Spectra from the pulsar were extracted from a $2''$ radius aperture and the background estimated from a $2'' < r < 4''$ annular region, using a minimum of 50 cts bin^{-1}. No significant spectral changes were detected within the four 2006 observations and these spectra were fit simultaneously to a piled-up power-law model with the absorbing column fixed at N_H=4$\times$10^{22} cm^{-2}. This provides a best-fit photon index, Γ, for the 2000 and 2006 observations of $1.17^{+0.15}_{-0.12}$ and $1.89^{+0.04}_{-0.06}$, respectively (3σ errors). Despite the pile-up, the 2006 observations show a clear softening of the spectrum. In turn, the unabsorbed fluxes in units of 10^{-11} erg s^{-1} cm^{-2} for the 2000 (2006) observations were $0.10^{+0.01}_{-0.01}$ ($1.7^{+0.8}_{-0.5}$) in the 0.5–2 keV range, and $0.42^{+0.16}_{-0.05}$ ($2.3^{+1.4}_{-0.7}$) in the $2-10$ keV range (3σ errors). Due to the high count rate in the 2006 observations, significant emission from the pulsar was detected during the readout interval, resulting in a "readout streak" that contains un-piled, real events from the source. The power-law spectral parameters derived using these data are in agreement with those listed above.