The new magnetar Swift J1830.7−0645 in outburst

F. Coti Zelati,1,2 A. Borghese,1,2 G. L. Israel,3 N. Rea,1,2 P. Esposito,4,5 M. Pilia,6 M. Burgay,6 A. Possenti,6,7 A. Corongiu,6 A. Ridolfi,6,8 C. Dehman,1,2 D. Viganò,1,2 R. Turolla,9,10 S. Zane,10 A. Tiengo,4,5,11 and E. F. Keane12

1 Institute of Space Sciences (ICE, CSIC), Campus UAB, C/Can Magrans s/n, 08193, Barcelona, Spain
2 Institut d’Estudis Espacials de Catalunya (IEEC), Carrer Gran Capità 2-4, 08034 Barcelona, Spain
3 INAF–Osservatorio Astronomico di Roma, via Frascati 33, 00078 Monteporzio Catone, Italy
4 Scuola Universitaria Superiore IUSS Pavia, Palazzo del Broletto, Piazza della Vittoria 15, 27100 Pavia, Italy
5 INAF–Istituto di Astrofisica Spaziale e Fisica Cosmica di Milano, via A. Corti 12, 20133 Milano, Italy
6 INAF–Osservatorio Astronomico di Cagliari, Via della Scienza 5, 09047 Selargius, Italy
7 Department of Physics, Università di Cagliari, S.P. Monserrato-Sestu km 0,700, 09042 Monserrato, Italy
8 Max Planck Institute für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
9 Dipartimento di Fisica e Astronomia ‘Galileo Galilei’, Università di Padova, via F. Marzolo 8, 35131 Padova, Italy
10 Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK
11 Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Pavia, via A. Bassi 6, 27100 Pavia, Italy
12 SKA Organisation, Jodrell Bank, Macclesfield, Cheshire, SK11 9FT, UK

Submitted to ApJL

ABSTRACT

The detection of a short hard X-ray burst and an associated bright soft X-ray source by the Swift satellite in October 2020 heralded a new magnetar in outburst, Swift J1830.7−0645. Pulsations at a period of ∼10.4 s were detected in prompt follow-up X-ray observations. We present here the analysis of the Swift/BAT burst, of XMM–Newton and NuSTAR observations performed at the outburst peak, and of a Swift/XRT monitoring campaign over the subsequent month. The burst was single-peaked, lasted ∼6 ms, and released a fluence of ≈5 × 10^{-9} \text{erg cm}^{-2} (15–50 keV). The spectrum of the X-ray source at the outburst peak was well described by an absorbed double-blackbody model plus a flat power-law component detectable up to ∼25 keV. The de-absorbed X-ray flux decreased from ∼5 × 10^{-11} \text{erg cm}^{-2} \text{s}^{-1} to ∼2.5 × 10^{-11} \text{erg cm}^{-2} \text{s}^{-1} one month later (0.3–10 keV). Based on our timing analysis, we estimate a dipolar magnetic field ≈5.5 × 10^{15} G at pole, a spin-down luminosity ≈2.4 × 10^{32} \text{erg s}^{-1}, and a characteristic age ≈24 kyr. The spin modulation pattern appears highly pulsed in the soft X-ray band, and becomes smoother at higher energies. Several short X-ray bursts were detected during our campaign. No evidence for periodic or single-pulse emission was found at radio frequencies in observations performed with the Sardinia Radio Telescope and Parkes. According to magneto-thermal evolutionary models, the real age of Swift J1830 is close to the characteristic age, and the magnetic field at birth was slightly larger, ∼10^{15} G.

Keywords: Magnetars(992) — Neutron stars(1108) — Transient sources(1851) — X-ray bursts(1814)

1. INTRODUCTION

On 2020 October 10 at 14:49:24 UT, the Burst Alert Telescope (BAT) on board the Neil Gehrels Swift Observ-
An X-ray periodic signal at ∼10.4 s was detected in the XRT data (Gogus et al. 2020a) and confirmed later by NICER observations (Younes et al. 2020). The burst properties, the periodicity detected in the prompt follow-up observations, and the proximity of the source to the Galactic plane (Galactic latitude $b \sim 1.5^\circ$) point to a newly discovered magnetar in outburst.

The term ‘magnetar’ was coined almost three decades ago to identify isolated neutron stars (NSs) ultimately powered by dissipation of their own magnetic energy, which usually implies that they are endowed with huge magnetic fields, up to $\sim 10^{15} \, \text{G}$ (Duncan & Thompson 1992). A large fraction of the ∼30 magnetars known to date (Olausen & Kaspi 2014) have been discovered just over the past two decades, through their distinctive high-energy phenomenology: bursts of X-ray/gamma-ray emission and/or enhancements of their persistent X-ray luminosity, dubbed ‘outbursts’ (see Kaspi & Beloborodov 2017; Esposito et al. 2021). The bursts are comparatively brief episodes lasting from milliseconds to hundreds of seconds, and reaching X-ray peak luminosities within the interval $10^{39} - 10^{47} \, \text{erg s}^{-1}$ (e.g., Colazzi et al. 2015). The outbursts are instead long-lasting events where the X-ray luminosity firstly rises to values in the range $10^{34} - 10^{36} \, \text{erg s}^{-1}$, and then decreases on time scales that can be as long as years. Besides, magnetars might not attain the same luminosity level at the end of distinct outbursts (Coti Zelati et al. 2018, 2020).

This Letter reports on: (i) the properties of the X-ray bursts detected from Swift J1830 by the Swift/BAT; (ii) quasi-simultaneous XMM–Newton and NuSTAR observations performed within ∼2 days after the first BAT burst; (iii) a Swift/XRT monitoring campaign covering the first month since the outburst onset; (iv) a search for short bursts in the X-ray time series ($\S 2$); (v) radio observations with the Sardinia Radio Telescope and Parkes ($\S 3$). Discussion and conclusions follow ($\S 4$).

2. X-RAY EMISSION

2.1. Observations and Data Analysis

Table 1 reports a journal of the X-ray observations. Data reduction was performed using tools incorporated in HEASOFT (v.6.28) and the Science Analysis Software (v.19) with the latest calibration files. Photon arrival times were barycentered using the Chandra position (Gogus et al. 2020b), RA = $18^h30^m41.6^s4$, Dec = $06^\circ45.16'9$ (J2000.0; uncertainty of 0.8′’ at 90% confidence level$^2$) and the JPL planetary ephemeris DE-405. Hereafter, all uncertainties are quoted at 1σ c.l.

2.1.1. Swift

For the burst that revealed Swift J1830 by alerting the BAT and another one detected on 2020 November 5, we extracted mask-tagged light curves and spectra using the standard tools in the FTOOLS software package. Swift J1830 was observed 14 times with the XRT (Burrows et al. 2005) configured either in photon counting (PC; timing resolution of 2.5 s), or windowed timing (WT; 1.8 ms) mode. The source photons were extracted from a 20-pixel circular region (1 pixel=2′′36). Background events were collected from a region of the same size for WT-mode data and an annulus with radii 40–80 pixels for PC-mode data. In the first pointing, photons within the inner 4 pixels of the source point spread function were removed to minimize pile-up effects.

2.1.2. XMM–Newton

Swift J1830 was observed with the European Photon Imaging Cameras (EPIC) on board XMM–Newton on 2020 October 11–12, for an exposure time of 23.6 ks. The EPIC-pn (Strüder et al. 2001) and the MOS (Turner et al. 2001) cameras were operating in Small Window mode (SW; timing resolutions of 5.7 ms and 0.3 s, respectively). Here, we consider only data acquired with the EPIC-pn, which provides the data set with the highest counting statistics owing to its larger effective area compared to the MOS cameras.

Raw data were processed following standard analysis procedures. No periods of high background activity were detected. The source events were selected from a 40″ circle and the background counts were accumulated from a closely circle of the same size. The response matrices and ancillary files were generated through the RMFGEN and ARFGEN tools, respectively. Background-subtracted and exposure-corrected light curves were extracted using the EPICLCCORR task.

2.1.3. NuSTAR

NuSTAR (Harrison et al. 2013) observed Swift J1830 on 2020 October 12 for an effective exposure time of 29.6 ks. We created cleaned event files and filtered out passages through the South Atlantic Anomaly using the tool NUPipeline with default options. For both focal plane modules (FPMA and FPMB), we collected the source counts within a circle of radius 100″, and estimated the background using a circle of the same size on

$^1$ Tohuvavohu (2020) reported the discovery in an offline search of the BAT data of another burst from Swift J1830, which, however, did not result in a detector trigger.

$^2$ The uncertainty is dominated by the satellite absolute positional accuracy. See https://cxc.harvard.edu/cal/ASPECT/celmon/.
Table 1. Observation Log

| X-ray Instrument | Obs.ID | Start (UTC) | Stop (UTC) | Exposure | Net Count Rate | Flux (Obs / Dc-abs) |
|------------------|--------|-------------|------------|----------|----------------|-------------------|
| ROSAT/PSPC       | rp50091209 | 1991-04-03 20:34:56 | 1991-04-03 23:04:12 | 4.5 | <0.98 | <0.01 / <0.05 |
| Swift/XRT (PC)   | 00999571000 | 2020-10-10 14:51:20 | 2020-10-16 23:30:29 | 1.7 | 0.47 ± 0.02 | (4.0 ± 0.2) / (5.0 ± 0.2) |
| Swift/XRT (PC)   | 00999571001 | 2020-10-10 17:53:14 | 2020-10-10 22:20:35 | 4.5 | 0.42 ± 0.01 | (3.8 ± 0.1) / (4.6 ± 0.1) |
| XMM-Newton/EPIC-pn (SW) | 0872590051 | 2020-10-11 21:07:13 | 2020-10-12 03:41:12 | 16.5 | 7.09 ± 0.02 | (3.96 ± 0.02) / (5.11 ± 0.02) |
| NuSTAR/FPMA      | 06963133002 | 2020-10-12 07:46:09 | 2020-10-12 23:26:09 | 29.6 | 0.715 ± 0.005 | (3.96 ± 0.02) / (5.11 ± 0.02) |
| Swift/XRT (WT)   | 00999571003 | 2020-10-15 01:53:03 | 2020-10-15 20:35:55 | 2.1 | 0.69 ± 0.02 | (4.1 ± 0.2) / (5.1 ± 0.2) |
| Swift/XRT (WT)   | 00999571004 | 2020-10-16 10:35:46 | 2020-10-17 19:04:56 | 2.6 | 0.69 ± 0.02 | (3.7 ± 0.2) / (4.6 ± 0.2) |
| Swift/XRT (WT)   | 00999571005 | 2020-10-19 01:48:46 | 2020-10-19 22:03:56 | 3.3 | 0.66 ± 0.02 | (3.5 ± 0.1) / (4.4 ± 0.1) |
| Swift/XRT (WT)   | 00999571006 | 2020-10-20 11:33:32 | 2020-10-23 14:51:44 | 0.9 | 0.55 ± 0.03 | (3.3 ± 0.1) / (4.2 ± 0.1) |
| Swift/XRT (WT)   | 00013840001 | 2020-10-29 04:35:55 | 2020-10-29 22:34:56 | 2.9 | 0.51 ± 0.02 | (2.9 ± 0.1) / (3.9 ± 0.2) |
| Swift/XRT (WT)   | 00013840002 | 2020-11-01 15:23:43 | 2020-11-02 11:00:56 | 4.1 | 0.42 ± 0.01 | (3 ± 0.2) / (3.8 ± 0.2) |
| Swift/XRT (WT)   | 00013840003 | 2020-11-04 10:24:01 | 2020-11-04 23:19:50 | 2.8 | 0.47 ± 0.01 | (2.5 ± 0.1) / (3.2 ± 0.1) |
| Swift/XRT (PC)   | 01004219000 | 2020-11-05 02:24:07 | 2020-11-05 02:52:52 | 1.7 | 0.34 ± 0.01 | (2 ± 0.1) / (3.2 ± 0.1) |
| Swift/XRT (WT)   | 00013840004 | 2020-11-06 11:42:27 | 2020-11-06 18:35:56 | 3.8 | 0.48 ± 0.01 | (2.6 ± 0.1) / (3.9 ± 0.1) |
| Swift/XRT (WT)   | 00013840005 | 2020-11-10 05:01:02 | 2020-11-10 10:07:56 | 3.9 | 0.44 ± 0.01 | (3.2 ± 0.1) / (2.9 ± 0.1) |
| Swift/XRT (PC)   | 01005428000 | 2020-11-11 09:46:28 | 2020-11-11 10:15:10 | 1.7 | 0.37 ± 0.01 | (3 ± 0.1) / (3.6 ± 0.1) |
| Swift/XRT (WT)   | 00013840006 | 2020-11-13 01:34:21 | 2020-11-13 13:09:56 | 3.6 | 0.33 ± 0.01 | (2.0 ± 0.1) / (2.6 ± 0.1) |

the same chip. The source was detected up to an energy of ~25 keV in the FPMA and ~20 keV in the FPMB. We ran the tool NUPRODUCTS to extract light curves and spectra, and to generate response files. We observed an apparent discrepancy between the FPMA and FPMB spectra at high energies (see Hattori et al. 2020 for a recent assessment of systematic differences for NuSTAR spectra). A power-law model fit to the spectra above 10 keV gives indeed photon indices of $\Gamma_A = 2.8 \pm 0.2$ (FPMA) and $\Gamma_B = 3.5 \pm 0.3$ (FPMB), and a flux discrepancy of ~20%. Keeping in mind this systematic uncertainty, in the following we will focus on the data sets from the FPMA, which detected a significant signal over a broader energy range.

2.2. Results

2.2.1. BAT Bursts Properties

Figure 1 shows the time evolution of the burst detected on 2020 October 10 in the 15–50 keV band (no emission is detected at higher energies). The event was single-peaked and had a total duration, as computed from a Bayesian blocks analysis with the BATTBLOCKS tool, of $6 \pm 1$ ms ($T_{90} = 5 \pm 1$ ms). The spectrum extracted from the whole interval, similarly to standard magnetar bursts seen at hard X-rays, can be described in the 15–50 keV band by simple models, such as a blackbody with temperature $K_T = 8.0^{+1.6}_{-1.2}$ keV (with reduced $\chi^2$ of $\chi^2_r = 1.05$ for 14 degrees of freedom (d.o.f.)) or a power law with $\Gamma = 1.9 \pm 0.5$ ($\chi^2_r = 1.12$ for 14 d.o.f.). For the blackbody model, the average flux was $7.6^{+0.4}_{-0.3} \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$, corresponding to a fluence of $\sim 4.6 \times 10^{-7}$ erg cm$^{-2}$ (15–50 keV). The second burst detected on 2020 November 5 was longer (25 ± 5 ms, $T_{90} = 21 \pm 5$ ms) and harder, being visible in the light curve up to ~150 keV. Also in this case, the adoption of
blackbody model resulted in the best fit, with $\chi^2 = 0.83$ for 56 d.o.f., and $kT = 9.8 \pm 0.7$ keV. The average flux was $(1.3 \pm 0.1) \times 10^{-6}$ erg cm$^{-2}$s$^{-1}$, while the fluence was $\sim 3.2 \times 10^{-8}$ erg cm$^{-2}$ (15–150 keV).

2.2.2. X-ray Monitoring and Archival Observations

We performed the spectral analysis using the XSPEC package (Arnaud 1996) adopting the TBABS model (Wilms et al. 2000) to describe the interstellar absorption. Firstly, we fit the broad-band spectrum extracted from the quasi-simultaneous EPIC-pn and NuSTAR/FPMA data sets using models comprising different combinations of blackbody and power-law components. We included a constant term in the fits to account for inter-calibration uncertainties between the two instruments, deriving a mismatch of <5% for all the tested models. The best description of the data was provided by an absorbed double-blackbody model plus a power-law component accounting for emission at energies above $\sim 12$ keV (Figure 1), giving $\chi^2 = 0.99$ for 248 d.o.f. and a null hypothesis probability nhp = 0.64. Best-fitting parameters were: absorption column density $N_H = (1.07 \pm 0.02) \times 10^{22}$ cm$^{-2}$, blackbody temperatures and radii $kT_{BB,W} = 0.45 \pm 0.01$ keV, $R_{BB,W} = 5.6 \pm 0.3$ km for the warm component and $kT_{BB,H} = 1.11 \pm 0.01$ keV, $R_{BB,H} = 1.53 \pm 0.03$ km for the hot component (assuming a distance of 10 kpc), and $\Gamma = 0.5^{+0.4}_{-0.3}$. The observed and de-absorbed flux were $(4.11 \pm 0.03) \times 10^{-11}$ and $(5.58 \pm 0.03) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the 0.3–25 keV range, with a contribution of the power-law component of $\sim 7\%$ in the same band.

Then, we fit an absorbed double-blackbody model to all Swift/XRT data, fixing the column density at $N_H = 1.07 \times 10^{22}$ cm$^{-2}$, and allowing all other parameters to vary across the data sets. The inset in the left panel of Figure 1 shows the evolution of the de-absorbed flux of Swift J1830 derived from the above model. The flux decreased by a factor of $\sim 2$ along our campaign, from $\sim 5 \times 10^{-11}$ erg cm$^{-2}$s$^{-1}$ at peak to $\sim 2.5 \times 10^{-11}$ erg cm$^{-2}$s$^{-1}$ about one month later (0.3–10 keV). Its time evolution can be adequately described so far by an exponential function with $\epsilon$-folding time $\tau = 55 \pm 2$ d ($\chi^2 = 1.42$ for 13 dof; Figure 1).

Swift J1830 was in the field of view of ROSAT/PSPC in a pointing performed on April 3, 1991 (see Table 1). The source is not detected in these data. We set an upper limit of 0.008 counts s$^{-1}$ on the net count rate (3$\sigma$ c.l.; 0.1–2.4 keV). Assuming emission from the entire surface ($R_{NS} = 10–15$ km) and a source distance of $\approx 10$ kpc, we estimate that the blackbody temperature should be $\leq 0.15$ keV to be consistent with the above limit. The corresponding limits on the observed and de-absorbed flux are $F_{X,obs} < 8 \times 10^{-14}$ erg cm$^{-2}$s$^{-1}$ and $F_{X,deabs} < 1.5 \times 10^{-12}$ erg cm$^{-2}$s$^{-1}$ (0.3–10 keV).

2.2.3. Timing Analysis and Phase-resolved Spectroscopy

The EPIC-pn, Swift/XRT and NuSTAR source event files were used to study the magnetar timing properties. We built up a phase-coherent timing solution starting
Figure 2. Left: Energy-resolved background-subtracted pulse profiles of Swift J1830 extracted from XMM–Newton/EPIC-pn (gray) and NuSTAR/FPMA (red) data. The best-fitting models obtained by using seven sinusoidal components (fundamental plus harmonics) for EPIC-pn and a single sinusoidal component (fundamental) for the FPMA are indicated with solid lines. The corresponding pulsed fraction values (or the 3σ upper limit for the 15–25 keV range) are reported in each panel. Right: Results of the spin phase-resolved spectroscopy of EPIC-pn data in the 0.3–10 keV range. From top to bottom: background-subtracted pulse profile; blackbody temperature, radius (assuming a distance of 10 kpc; see §4) and 0.3–10 keV de-absorbed flux for the warm (light gray) and hot (dark gray) components; hot-to-warm blackbody unabsorbed flux ratio; nhp values derived from the χ² and the d.o.f. of the fit of each spectrum. All uncertainties are at 1σ c.l.. Two spin cycles are shown for clarity.

from the period inferred from the EPIC-pn data sets (those with the largest statistics), $P = 10.41572(1)\text{ s}$. Within a baseline of about 34 days (October 10 – November 13), we clearly detected a first period derivative component in the signal phase history, and derived the following timing solution: $P = 10.415724(1)\text{ s}$; $\dot{P} = (7 \pm 1) \times 10^{-12}\text{ s s}^{-1}$ and reference epoch $T_0 = 59133.0\text{ MJD}$. The $\dot{P}$ value is in agreement with that derived by Ray et al. (2020) using NICER data sets. Our timing solution implies a r.m.s. variability of $\sim 145\text{ ms}$, corresponding to a timing noise level <2%, similar to the range of values observed in other isolated NSs. We set a 3σ upper limit on the second period derivative of $|\ddot{P}| < 2 \times 10^{-17}\text{ s s}^{-2}$.

Figure 2 shows the background-subtracted light curves extracted from the EPIC-pn and NuSTAR data sets over different energy intervals, folded using the above ephemeris. Pulsed emission was detected up to an energy of $\sim 15\text{ keV}$. The pulse profile displays an apparent complex morphology below 10 keV, with a pronounced dip close to the main peak, a weaker peak in the rising part of the profile, and small-amplitude structures at minimum (seemingly less prominent above $\sim 4\text{ keV}$). The profile appears to evolve to a relatively simpler shape at higher energies in the 12–15 keV range. The pulse peak in this range lags the main peak observed at lower energies by 0.11 ± 0.06 spin phase cycles. The background-subtracted peak-to-peak semi-amplitude increases from...
and XMM–Newton light curves (Figure 3). No bursts were found in the total number of time bins and durations, except for a 3σ upper limit of 20% in the 15–25 keV range (Figure 2). The marked changes in the pulse profile amplitude at energies where the power-law spectral component dominates the source emission (Figure 1) indicate that the power-law tail is also pulsed, though to a much smaller extent than the low-energy blackbody components. This and the slight phase shift observed point to different emission regions for the power-law and blackbody components.

We performed a phase-resolved spectral analysis over the 0.3–10 keV energy range using the EPIC-pn data. We extracted spectra from 50 phase intervals of width 0.02 rotational cycles, and fitted them using an absorbed double-blackbody model. In the fits, the column density was held fixed at the phase-averaged value \( N_H = 1.07 \times 10^{22} \text{ cm}^{-2} \); \( \sigma_{2.2.2} \), while all other parameters were allowed to vary. Figure 2 shows the evolution of the spectral parameters and de-absorbed fluxes of both thermal components, as well as their flux ratio, along the rotational phase. The complex spin modulation pattern for the soft X-ray emission can be ascribed to changes in the blackbody radius of both components. The smaller-hotter region traces more closely the fine structures seen in the pulse profile (e.g., the dip close to the peak; Figure 2). On the other hand, the scarce counting statistics available in the range 12–15 keV (less than 200 net counts in the FPMA) precludes an assessment of possible variability of the power-law slope along the rotational phase.

2.2.4. Search for Short X-ray Bursts

Short X-ray bursts were searched for by applying the procedure described by Borghese et al. (2020). We extracted light curves with different time resolutions (2\(^{-4}\), 2\(^{-5}\), 2\(^{-6}\))s to improve sensitivity to bursts of different durations, except for Swift/XRT PC-mode light curves that were binned at the timing resolution (2.5073s). For each observation, we calculated the Poisson probability of an event to be a random fluctuation with respect to the average number of counts per bin. Any bin with a probability smaller than \( 10^{-4} (N \times N_{\text{trials}})^{-1} \), where \( N \) is the total number of time bins and \( N_{\text{trials}} \) is the number of timing resolutions used in the search, was flagged as part of a burst. We detected 15 bursts in the Swift/XRT light curves (Figure 3). No bursts were found in the XMM–Newton and NuSTAR data sets.

3. RADIO SEARCHES

Table 1 reports a log of the radio observations, performed using the Sardinia Radio Telescope (SRT; Bolli et al. 2015; Prandoni et al. 2017) and Parkes.

3.1. Sardinia Radio Telescope Observations

The SRT observed Swift J1830 at 1.5 GHz (L-band) on October 11 for 2.7 h and at 6.8 GHz (C-band) on October 21, October 30, and November 6, for a total exposure of 22.5 h. Data were recorded with the ATNF PDFB backend in search mode over a bandwidth of 500 MHz in L-band and 900 MHz in C-band, with a spectral resolution of 1 MHz. Total intensity data were 2-bit sampled every 0.1 ms for L-band and 0.125 ms for C-band.

All data were folded using the X-ray ephemeris and searched over a dispersion measure (DM) range 0–1200 pc cm\(^{-3}\) and a spin period range of ±1 ms around the nominal value (after removing the most prominent radio frequency interference; RFI), using the software packages DSpSR (van Straten & Bailes 2011) and PSRCHIVE (Hotan et al. 2004). No pulsations were detected down to a folded \( S/N \sim 10 \). The corresponding flux density upper limits are reported in Table 1.

A search for bursts was performed on all data using the SPANDAK pipeline (Gajjar et al. 2018), sampling a DM range 0–1200 pc cm\(^{-3}\). After dedispersion, the time series were searched for pulses using matched-filtering with a maximum window size of 32 ms. After a first automatic sifting of the generated candidates, visual inspection was performed on the events that passed the selection. No bursts were found at either L- or C-band.

3.2. Parkes Observations

The Parkes radio telescope observed Swift J1830 on October 12, starting at 08:04:24 UT for 2.9 h, simultaneously with NuSTAR. Data were recorded with the ultra-wide-bandwidth low-frequency receiver (UWL; Hobbs et al. 2020) over a bandwidth of 3328 MHz centered at 2368 MHz. Full Stokes data were 4-bit sampled every 0.128 ms. Four separate data sets covering different sub-bands were created with different spectral resolutions so as to achieve a maximum broadening of a few ms for a signal with DM=600 pc cm\(^{-3}\) (band b0, from 704 to 1216 MHz, split into 2048 frequency channels; b1, 1216–1984 MHz, 768 channels; b2, 1984–2752 MHz, 384 channels; b3, 2752–4032 MHz, 320 channels).

To search for persistent pulsations, the data of the sub-bands were folded using the X-ray ephemeris. After RFI removal, the frequency resolution of the folded data was scaled uniformly down to 4 MHz, and data were summed together. A search over a DM range 0–1200 pc cm\(^{-3}\) spanning ±1 ms around the nominal spin period was performed on the entire observing band-

\(^3\)This is the maximum value expected for our Galaxy in the direction of Swift J1830, according to the NE2001 electron density model (Cordes & Lazio 2002).
width. No pulsations were detected down to a folded $S/N=10$, implying a flux density upper limit of $\sim16\mu$Jy, assuming a flat spectrum across the UWL band.

The single pulse analysis was performed using the procedure described in §3.1 and the same parameters. The sub-banding did not affect the search since we are looking for impulsive bursts. After the RFI removal, the data were dedispersed from 0 to 1200 pc cm$^{-3}$. No bursts were found at any band.

4. DISCUSSION

In October 2020, Swift J1830 entered its first detected outburst phase, revealing to be a new Galactic magnetar. Besides the short X-ray burst that marked the beginning of the outburst (Page et al. 2020), the source emitted two additional hard X-ray bursts during our monitoring campaign (Gropp et al. 2020a,b).

This is a distinctive phenomenology usually observed in magnetars during an active phase (Coti Zelati et al. 2018). Our campaign allowed to measure the spin period ($P = 10.415724(1)$ s) and its first derivative ($\dot{P} = (7 \pm 1) \times 10^{-12}$ s s$^{-1}$) at the outburst peak (§2.2.3), hence to estimate a surface dipolar magnetic field $B_{\text{dip}} \sim 6.4 \times 10^{19}(PP)^{1/2} \approx 5.5 \times 10^{14}$ G at pole (using the vacuum dipole formula), a spin-down luminosity $\dot{E}_{\text{rot}} = 4\pi^2 I P \dot{P} \approx 2.4 \times 10^{32}$ erg s$^{-1}$ and a characteristic age $\tau_c = P/2\dot{P} \approx 24$ kyr.

By comparing the column density derived from our spectral fits ($N_H = 1.07 \times 10^{22}$ cm$^{-2}$) with that expected within the Galaxy in the direction of the source (Willingale et al. 2013), we estimate a distance $D \approx 10$ kpc. Assuming isotropic emission, the X-ray luminosity at the outburst peak is then $L_{\text{X},p} \sim 6 \times 10^{35} d_{10}^2$ erg s$^{-1}$ (0.3–10 keV; $d_{10} = D/10$ kpc), a factor of $\sim 2500$ larger

Figure 3. Light curves of Swift J1830 extracted from the Swift/XRT data in which we detected bursts (0.3–10 keV range; time bin: 62.5 ms). All events fulfilling our detection criterion are marked by arrows.
Figure 4. Quiescent X-ray luminosity as a function of the spin period for magnetars, including Swift J1830 (in bold). Circles mark radio-loud magnetars. The gray shaded region shows the magneto-thermal evolutionary path of Swift J1830 according to the model discussed in the text. Values are taken from http://magnetars.ice.csic.es/.

than the spin-down luminosity. The limit we derived for the quiescent X-ray luminosity is $L_{X,q} < 2 \times 10^{34} d_{10}^2 \text{erg s}^{-1}$ (0.3–10 keV; see §2.2.2).

We studied the evolutionary history of Swift J1830 using a two-dimensional magneto-thermal code (Viganò et al. 2012, 2013; Viganò et al. submitted). We used crustal-confined models consisting of an initial poloidal dipolar field ($B_{dip,in}$) plus a toroidal field ($B_{tor,in}$), and assumed an equal amount of magnetic energy in the two components. The initial configuration that matches the current $P$ and $\dot{P}$ and the limit on $L_{X,q}$ more closely comprises $B_{dip,in} \sim 10^{15} \text{G}$ and $B_{tor,in} \sim 10^{16} \text{G}$. By modelling this evolution, we obtain a thermal age for Swift J1830 of $\tau_{th} \sim 23 \text{kyr}$, similar to its characteristic age. The good agreement between $\tau_{th}$ and $\tau_c$ is due to the fact that dissipation of the magnetic field is not yet substantial at this evolutionary stage. At later stages, $\tau_c$ will overestimate the true age because the electromagnetic torque decreases in time due to magnetic field dissipation, while $\tau_{th}$ usually remains consistent with the true age. The current quiescent bolometric luminosity is also expected to be just below our current upper limit.

From its properties and simulated history, we find that Swift J1830 is a middle age magnetar that had a relatively strong magnetic energy at birth. The gray shaded region in Figure 4 shows the evolution of the spin period and luminosity of Swift J1830 (taking into account uncertainties due to the assumption of light or heavy elements in the envelope), compared with current values for other magnetars. To model the evolutionary path of a magnetar, we need to match its $L_{X,q}$, $P$ and $\dot{P}$ (or $B_{dip}$) at once. The properties of Swift J1830 at birth
might be similar to those of CXOU J171405.7−381031, which is now at an earlier stage of a similar evolutionary scenario. On the other hand, XTE J1810−197, although having a luminosity and spin period potentially falling on the same evolutionary path, has a magnetic field which is not compatible with this scenario, it is already lower at a younger age.

The X-ray emission properties observed from Swift J1830 soon after the outburst onset are in line with those of other magnetars (Coti Zelati et al. 2018 and references therein), and fit well within the resonant Compton scattering scenario (RCS; Thompson et al. 2002; Rea et al. 2008; see also Turolla et al. 2015 and references therein). The dominance of the thermal over the non-thermal (power-law) component (§2.2.2) suggests that the magnetospheric twist is restricted to a bundle of current-carrying field lines. Ohmic dissipation of the returning currents on the star surface leads to the appearance of localized hot spots (Beloborodov 2009). Heated regions may form on the surface also as a consequence of heat released deeper in the crust by local dissipation of magnetic energy (Pons & Rea 2012). In this respect, our analysis suggests the existence of two heated regions of different temperatures and sizes on the surface of Swift J1830: an extended warm region (average blackbody temperature $\sim 0.45$ keV and radius $\sim 6$ km), and a small hot region (temperature $\sim 1.1$ keV and radius $\sim 1.5$ km). According to our analysis, the modulation of the light curve is (almost) entirely due to the change of the visible area of these regions, the temperatures being fairly constant along the spin phase (§2.2.3). This is indicative of a scenario in which the hot and the warm regions are not spatially separated. A more plausible picture is that what we actually see is a single heated spot with a temperature gradient. Indeed, recent 3D simulations have shown that heat injected in the crust of a magnetar flows anisotropically to the surface, giving rise to non-uniform hot spots of complex shape (De Grandis et al. 2020). Soft, thermal photons coming from a small spot can produce a complex pulse profile with a high pulsed fraction (Geppert & Viganò 2014; Igoshev et al. 2020), which would be smaller ($\lesssim 20\%$) in the case of two circular, antipodal hot spots (Turolla & Nobili 2013). The decrease of the pulsed fraction in going from lower to higher energies may be explained within the RCS scenario. Above $\sim 10$ keV, in fact, photons are mostly in the power-law tail and suffered resonant scatterings higher up in the magnetosphere ($R \approx 10R_{NS}$), which tends to wash out the imprint of the (pulsed) primary emission.

Our non-detection of radio pulsations from Swift J1830 is not that surprising per se. Similarly to canonical radio pulsars, radio-loud magnetars are generally characterized by high spin-down luminosities $\dot{E}_{\text{rot}} \gtrsim 10^{33}$ erg s$^{-1}$, implying $L_{X, q}/\dot{E}_{\text{rot}} < 1$ (Rea et al. 2012; the only outlier being XTE J1810−197). A reliable estimate of $L_{X, q}/\dot{E}_{\text{rot}}$ for Swift J1830 is difficult owing to uncertainties on the distance and the non-detection of the source in pre-outburst X-ray data. However, if its quiescent luminosity is not much below our quoted limit, it would have $L_{X, q}/\dot{E}_{\text{rot}} > 1$, in line with being radio-silent. Alternatively, Swift J1830 might be radio-loud but undetectable due to unfavourable beaming.

Future high-sensitive X-ray observations will be key in mapping the evolution of the heated spot on the star surface and the long-term contribution of magnetospheric currents to the broad-band X-ray emission of Swift J1830.

ACKNOWLEDGMENTS

We thank N. Schartel and F. Harrison for scheduling Target of Opportunity observations with XMM–Newton and NuSTAR in the Director’s Discretionary Time. This research is based on observations with XMM–Newton (ESA/NASA), NuSTAR (CalTech/NASA/JPL) and Swift (NASA/ASI/UKSA) and on data retrieved through the NASA/GSFC’s HEASARC archives. The Sardinia Radio Telescope is funded by the Department of Universities and Research (MIUR), the Italian Space Agency (ASI), and the Autonomous Region of Sardinia (RAS), and is operated as a National Facility by the National Institute for Astrophysics (INAF). We used data collected at the Parkes radio telescope (proposal P1083), part of the Australia Telescope National Facility which is funded by the Australian Government for operation as a National Facility managed by CSIRO. We acknowledge the Wiradjuri people as the traditional owners of the Observatory site. We acknowledge the support of the PHAROS COST Action (CA16214). F.C.Z and A.B are supported by Juan de la Cierva fellowships. F.C.Z, A.B, N.R, C.D and D.V are supported by the ERC Consolidator Grant “MAGNESIA” (nr.817661) and acknowledge funding from grants SGR2017-1383 and PGC2018-095512-BI00. G.L.I, R.T and A.T acknowledge financial support from the Italian MIUR through PRIN grant 2017LJ39LM. A.P, M.B and A.R gratefully acknowledge financial support from the research grant “iPeska” (P.I. Andrea Possenti) funded under the INAF national call PRIN-SKA/CTA with Presidential Decree 70/2016.
REFERENCES

Arnaud, K. A. 1996, in Astronomical Data Analysis Software and Systems V, Vol. 101, XSPEC: The First Ten Years, ed. G. H. Jacoby & J. Barnes (ASP, San Francisco), 17–20

Beloborodov, A. M. 2009, ApJ, 703, 1044 doi: 10.1088/0004-637X/703/1/1044

Biella, P., Orlati, A., Stringhetti, L., et al. 2015, Journal of Astronomical Instrumentation, 4, 1550008–880 doi: 10.1142/S2251171715500087

Borghese, A., Coti Zelati, F., Rea, N., et al. 2020, ApJL, 902, L2 doi: 10.3847/2041-8213/aba82a

Burrows, D. N., Hill, J. E., Nousek, J. A., et al. 2005, Space Science Reviews, 120, 165

Collazzi, A. C., Kouveliotou, C., van der Horst, A. J., et al. 2015, ApJS, 218, 11 doi: 10.1088/0067-0049/218/1/11

Cordes, J. M. & Lazio, T. J. W. 2002, astro-ph/0207156

Coti Zelati, F., Rea, N., Pons, J. A., Campana, S., & Esposito, P. 2018, MNRAS, 474, 961

Coti Zelati, F., Borghese, A., Rea, N., et al. 2020, A&A, 633, A31 doi:10.1051/0004-6361/201936317

De Grandis, D., Turolla, R., Wood, T. S., et al. 2020, ApJ, 903, 40 doi: 10.3847/1538-4357/abb6f9

Duncan, R. C. & Thompson, C. 1992, ApJL, 392, L9. doi:10.1086/186413

Esposito, P., Rea, N., & Israel, G. L. 2021, in Timing Neutron Stars: Pulsations, Oscillations and Explosions, ed. T. Belloni, M. Mendez, & C. Zhang, ASSL, Springer, in press (preprint: astro-ph/1803.05716)

Gajjar, V., Siemion, A. P. V., Price, D. C., et al. 2018, ApJ, 863, 2 doi: 10.3847/1538-4357/aad005

Geppert, U. & Viganò, D. 2014, MNRAS, 444, 3198 doi: 10.1093/mnras/stu1675

Gogus, E., Kouveliotou, C., & Younes, G. 2020a, The Astronomer’s Telegram, 14085

Gogus, E., Kouveliotou, C., & Younes, G. 2020b, The Astronomer’s Telegram, 14097

Gropp, J. D., Kennea, J. A., Klingler, N. J., et al. 2020a, GRB Coordinates Network, Circular Service, No. 28838, 28838

Gropp, J. D., Klingler, N. J., Kuin, N. P. M., et al. 2020b, GRB Coordinates Network, Circular Service, No. 28879, 28879

Harrison, F. A., Craig, W. W., Christensen, F. E., et al. 2013, ApJ, 770, 103

Hattori, S., Straal, S. M., Zhang, E., et al. 2020, arXiv:2009.10330

Hobbs, G., Manchester, R. N., Dunning, A., et al. 2020, PASA, 37, e012 doi: 10.1017/pasa.2020.2

Hotan, A. W., van Straten, W., & Manchester, R. N. 2004, PASA, 21, 302 doi: 10.1071/AS04022

Igoshev, A. P., Hollerbach, R., Wood, T., et al. 2020, Nature Astronomy doi: 10.1038/s41550-020-01220-z

Kaspi, V. M., & Beloborodov, A. M. 2017, ARA&A, 55, 261

Olausen, S. A. & Kaspi, V. M. 2014, ApJS, 212, 6. doi:10.1088/0067-0049/212/1/6

Page, K. L., Barthelmy, S. D., Klinger, N. J., et al. 2020, The Astronomer’s Telegram, 14083

Pons, J. A., & Rea, N. 2012, ApJL, 750, L6, doi: 10.1088/2041-8205/750/1/L6

Prandoni, I., Murgia, M., Tarchi, A., et al. 2017, A&A, 608, A40 doi: 10.1051/0004-6361/201630243

Ray, P. S., Younes, G., Guver, T., et al. 2020, The Astronomer’s Telegram, 14112

Rea, N., Zane, S., Turolla, R., et al. 2008, ApJ, 686, 1245 doi: 10.1086/591264

Rea, N., Pons, J. A., Torres, D. F., & Turolla, R. 2012, ApJL, 748, L12

Strüder, L., Briel, U., Dennerl, K., et al. 2001, A&A, 365, L18 doi: 10.1051/0004-6361:20000066

Thompson, C., Lyutikov, M., & Kulkarni, S. R. 2002, ApJ, 574, 332 doi: 10.1086/340586

Tohuvavohu, A. 2020, The Astronomer’s Telegram, 14088

Turner, M. J. L., Abbey, A., Arnaud, M., et al. 2001, A&A, 365, L27 doi: 10.1051/0004-6361:20000087

Turolla, R. & Nobili, L. 2013, ApJ, 768, 147 doi: 10.1088/0004-637X/768/2/147

Turolla, R., Zane, S., & Watts, A. L. 2015, Reports on Progress in Physics, 78, 116901 doi: 10.1088/0034-4885/78/11/116901

van Straten, W. & Bailes, M. 2011, PASA, 28, 1 doi: 10.1071/AS10021

Viganò, D., Pons, J. A., & Miralles, J. A. 2012, Computer Physics Communications, 183, 2042 doi: 10.1016/j.cpc.2012.04.029

Viganò, D., Rea, N., Pons, J. A., et al. 2013, MNRAS, 434, 123

Willingale, R., Starling, R. L. C., Beardmore, A. P., et al. 2013, MNRAS, 431, 394 doi: 10.1093/mnras/stt175

Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914

Younes, G., Guver, T., Wadiasingh, Z., et al. 2020, The Astronomer’s Telegram, 14086