X-ray and radio observations of the magnetar Swift J1834.9−0846 and its dust-scattering halo

P. Esposito,1⋆ A. Tiengo,1,2,3 N. Rea,4 R. Turolla,5,6 A. Fenzi,1,7 A. Giuliani,1 G. L. Israel,8 S. Zane,6 S. Mereghetti,1 A. Possenti,9 M. Burgay,9 L. Stella,8 D. Götz,10 R. Perna,11 R. P. Mignani6,12 and P. Romano13

1INAF – Istituto di Astrofisica Spaziale e Fisica Cosmica - Milano, via E. Bassini 15, I-20133 Milano, Italy
2IUSS – Istituto Universitario di Studi Superiori, piazza della Vittoria 15, I-27100 Pavia, Italy
3INFN – Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, via A. Bassi 6, I-27100 Pavia, Italy
4Institut de Ciències de l’Espai (IEEC–CSIC), Campus UAB, Torre C5, 2a planta, E-08193 Barcelona, Spain
5Dipartimento di Fisica e Astronomia, Università di Padova, via F. Marzolo 8, I-35131 Padova, Italy
6Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT
7Dipartimento di Fisica, Università degli Studi di Milano, via G. Celoria 16, I-20133 Milano, Italy
8INAF – Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio Catone, Italy
9INAF – Osservatorio Astronomico di Cagliari, loc. Poggio dei Pini, strada 54, I-09012 Capoterra, Italy
10AIM CEA/Irfu/Service d’Astrophysique, Orme des Merisiers, F-91191 Gif-sur-Yvette, France
11JILA and Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder, CO 80309, USA
12Institute of Astronomy, University of Zielona Góra, Lubuska 2, P-65265 Zielona Góra, Poland
13INAF – Istituto di Astrofisica Spaziale e Fisica Cosmica - Palermo, via U. La Malfa 153, I-90146 Palermo, Italy

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ABSTRACT

We present a long-term study of the 2011 outburst of the magnetar Swift J1834.9−0846 carried out using new Chandra observations, as well as all the available Swift, RXTE and XMM–Newton data. The last observation was performed on 2011 November 12, about 100 d after the onset of the bursting activity that had led to the discovery of the source on 2011 August 7. This long time-span enabled us to refine the rotational ephemeris and observe a downturn in the decay of the X-ray flux. Assuming a broken power law for the long-term light curve, the break was at ∼46 d after the outburst onset, when the decay index changed from α ∼ 0.4 to ∼4.5. The flux decreased by a factor of ∼2 in the first ∼50 d and then by a factor of ∼40 until 2011 November (overall, by a factor of ∼70 in ∼100 d). At the same time, the spectrum, which was well described by an absorbed blackbody all along the outburst, softened, the temperature dropping from ∼1 to ∼0.6 keV. Diffuse X-ray emission extending up to 20 arcsec from the source was clearly detected in all Chandra observations. Its spatial and spectral properties, as well as its time evolution, are consistent with a dust-scattering halo due to a single cloud located at a distance of ≈200 pc from Swift J1834.9−0846, which should be in turn located at a distance of ∼5 kpc. Considering the time delay of the scattered photons, the same dust cloud might also be responsible for the more extended emission detected in XMM–Newton data taken in 2011 September. We searched for the radio signature of Swift J1834.9−0846 at radio frequencies using the Green Bank Radio Telescope and in archival data collected at Parkes from 1998 to 2003. No evidence for radio emission was found, down to a flux density of 0.05 mJy (at 2 GHz) during the outburst and ∼0.2–0.3 mJy (at 1.4 GHz) in the older data.

Key words: stars: neutron—pulsars: general—dust, extinction—X-rays: individual: Swift J1834.9−0846.
1 INTRODUCTION

Anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs)\(^1\) are now generally accepted to be magnetars, i.e. neutron stars endowed with exceptionally strong magnetic fields (e.g. Mereghetti 2008). According to the magnetar model (Thompson & Duncan 1995, 1996; Thompson, Lyutikov & Kulkarni 2002), the decay of this magnetic field provides most of the energy that powers the emission of the neutron star. This scenario is supported by the fact that the surface dipole magnetic fields inferred under standard assumption for SGRs and AXPs from their rotational parameters are above, or at the high end of, those of ordinary pulsars. In fact they often exceed \(10^{14}\) G;\(^2\) although for SGR 0418–0525/39\(\times\)10\(^4\) cm\(^2\) was triggered by a short SGR-like burst (trigger 00458907; D’Elia et al. 2011) and \(\sim 330\) s after the trigger the X-Ray Telescope (XRT; Burrows et al. 2005) began observing the field of the burst. This led to the discovery of an X-ray source with a \(2–10\) keV flux of a few \(10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\) which was undetectable in previous observations of the field (with an upper limit on the flux of \(\lesssim 10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\); Kargaltsev et al. 2012). A few hours later, a second burst from the source direction was recorded by the Fermi/Gamma-ray Burst Monitor (GBM; Kargaltsev et al. 2012), while a further burst triggered the Swift/BAT again on 2011 August 29 (23:41:12.04\ UT, trigger 501752;Hoversten et al. 2011). This, together with the discovery of pulsations at 2.48 s with the Rossi X-Ray Timing Explorer (RXTE), confirmed the magnetar nature of the source (Gögüs & Kouveliotou 2011).

Subsequent observations allowed the determination of the spin-down rate of Swift J1834.9–0846 (\(\sim 8 \times 10^{-12}\) s s\(^{-1}\); Kuiper & Hermsen 2011; Kargaltsev et al. 2012). The 2–10 keV spectrum is very absorbed (\(N_H > 10^{23}\) cm\(^{-2}\)) and can be modelled by either a steep power law (\(\Gamma \sim 4\) or a hot blackbody (\(kT \sim 1\) keV; Kargaltsev et al. 2012). The decay of the X-ray flux for the first \(\sim 50\) d was consistent with a power law, \(F \propto t^{-\alpha}\) with \(\alpha \sim 0.5\).

Swift J1834.9–0846 was surrounded by an X-ray nebula with a complex spatial structure. The emission within 50 arcsec had a symmetrical shape and has been interpreted as a dust-scattering halo (Kargaltsev et al. 2012), while an asymmetrical structure which extended up to 2.5 arcmin from the point source has been attributed to a magnetar wind nebula (Younes et al. 2012).

Here we report on three new Chandra observations that, complementing the Chandra, Swift, RXTE and XMM–Newton data already analysed by Kargaltsev et al. (2012) and Younes et al. (2012), allowed us to characterize better the long-term spectral and temporal behaviour of Swift J1834.9–0846 and investigate in depth the nature of the diffuse emission. We also present the properties of the bursts observed with the Swift/BAT instrument, and the results of the search of the new SGR at radio frequencies using the 101-m diameter Robert C. Byrd Green Bank Telescope (GBT).

2 X-RAY OBSERVATIONS AND DATA REDUCTION

2.1 Chandra

The field of Swift J1834.9–0846 was serendipitously imaged by Chandra on 2009 June 6 during observations targeting the extended TeV source HESS J1834–087 (see Misanovic et al. 2011; Kargaltsev et al. 2012 for more details). Four more Chandra observations dedicated to Swift J1834.9–0846 (the first of which has already been published in Kargaltsev et al. 2012) were carried out; the first was performed 15 d after the SGR activation (see again Kargaltsev et al. 2012) and the last one after about 97 d (Table 1).

All these observations were carried out with the Advanced CCD Imaging Spectrometer (ACIS; Garnire et al. 2003) in Very Faint timed-exposure imaging mode. The source was positioned in the back-illuminated ACIS-S3 CCD (the only CCD used in these observations) at the nominal target position, and we used a sub-array of 1/8 (frame time: 0.44104 s). New level 2 event files were generated using the Chandra Interactive Analysis of Observation (CIAO) software version 4.4. We used the latest ACIS gain map, and applied the time-dependent gain and charge transfer inefficiency corrections. The data were then filtered for bad event grades.

2.2 Swift, RXTE and XMM–Newton

The first Swift/XRT observation started right after the Swift/BAT detection of the first burst on 2011 August 7 and further follow-up observations were carried out for a total of 78 ks (Table 1), covering the first 50 d after the beginning of the outburst. The XRT data were processed and filtered with standard procedures and criteria using FTOOLS tasks in the HEASOFT software package (v6.11) and the calibration files in the 2011-08-12 CALDB release. Similarly, BAT mask-tagged light curves, images and spectra were created using the standard BAT analysis software within FTOOLS.

An observing campaign of Swift J1834.9–0846 was carried out also with the RXTE. Here we report on the Proportional Counter Array (PCA; Jahoda et al. 2006) data collected within \(\sim 30\) d from the onset of the outburst (Obs. ID: 96434; see Table 1); after this period, the source flux become too low for the PCA sensitivity. We restricted our analysis to the data in Good Xenon mode, with a time resolution of 1 \(\mu\)s and 256 energy bins. The event-mode data were extracted in the 2–10 keV energy range from all active PCA units (in a given observation) and all layers, and binned into light curves of 0.1 s resolution using the standard RXTE analysis software within FTOOLS.

XMM–Newton observed the field of Swift J1834.9–0846 twice: on 2005 September 18 and on 2011 September 17, about 40 d after the discovery of the source (Table 1). In the first observation

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\(^1\) See the McGill Pulsar Group SGR/AXP catalogue at the web page [http://www.physics.mcgill.ca/~pulsar/magnetar/main.html](http://www.physics.mcgill.ca/~pulsar/magnetar/main.html)

\(^2\) For some magnetars the surface dipole magnetic field has been estimated also with other methods, always obtaining values of \(\sim 10^{14}\) G (e.g. Thompson & Duncan 1995, 2001; Vietri, Stella & Israel 2007; Israel et al. 2008).
Observations of Swift J1834.9–0846

3 RESULTS

3.1 Timing analysis

The arrival times of the 2–10 keV photons from Swift J1834.9–0846 were converted to the barycentre of the Solar system. Pulsations at ≈2.48 s were clearly detected in all the Swift (WT), XMM–Newton and Chandra data sets, and in the RXTE ones up to ≈30 d after the onset of the outburst.

The relative phases and amplitudes were such that, using a quadratic function (i.e. including a $P$ component), the signal phase evolution could be followed unambiguously for the observations from 2011 August 7 to 2011 October 2. The resulting fully coherent solution (ephemeris ‘A’, see Table 2 and Fig. 1) had a best-fitting period of $P = 2.482 \pm 0.009$ s and $\dot{P} = 8.28(2) \times 10^{-12}$ s s$^{-1}$ (uncertainties here are 1σ; MJD 55781.0 was used as reference epoch. These values are consistent with the measurement reported by Kuiper & Hermsen (2011) and Kargaltsev et al. (2012), who used in their fitting data with a shorter time-span (about 2 weeks and 1 month, respectively).

The inclusion of the last Chandra data set (Obs. ID: 14057, 2011 November 12) shows a significant disagreement (~9σ) with the value expected by extrapolating ephemeris A; a much better solution (the Fisher-test chance probability is $3.8 \times 10^{-4}$) can be obtained by including in the fit a higher order (cubic) term, corresponding to a $P$ component. This results in period and period derivative values which are only slightly different from those of ephemeris $A$, $P = 2.482 \pm 0.009$ s and $\dot{P} = 8.06(4) \times 10^{-12}$ s s$^{-1}$ (see Fig. 1 and Table 2 for the complete ephemeris, which we designate as ‘B’).

In Fig. 2 we show the Swift, XMM–Newton and Chandra background-subtracted light curves (2–10 keV) obtained folding the data on both ephemeris A and B. As can be seen from the plot, the profiles obtained with the different ephemeris are all very similar. To quantify any phase shifts, for each instrument we cross-correlated the A and B pulse profiles and the resulting peak in the
Table 2. Spin ephemeris of Swift J1834.9−0846. We also give for convenience the corresponding period $P$ and period derivative $\dot{P}$, as well as the derived characteristic age $\tau_c = P/(2\dot{P})$, dipolar magnetic field $B \approx 3c^3IP/8\pi^2R^6$ and rotational energy loss $\dot{E} = 4\pi^2IPP^3$ (here we took $R = 10$ km and $I = 10^{45}$ g cm$^2$ for the star radius and moment of inertia, respectively).

| Parameter | Ephemeris A | Ephemeris B |
|-----------|-------------|-------------|
| Range (MJD) | 55781.9–55836.7 | 55781.9–55877.6 |
| Epoch (MJD) | 55781.0 | 55781.0 |
| $\nu$ (Hz) | 0.402 852 210(7) | 0.402 852 17(1) |
| $\dot{\nu}$ (Hz s$^{-1}$) | $-1.344(3) \times 10^{-12}$ | $-1.308(7) \times 10^{-12}$ |
| $\ddot{\nu}$ (Hz s$^{-2}$) | $-1.2(3) \times 10^{-20}$ | $-1.2(3) \times 10^{-20}$ |

Derived parameters:

| Parameter | Ephemeris A | Ephemeris B |
|-----------|-------------|-------------|
| $P$ (s) | 2.482 299 90(4) | 2.482 300 17(7) |
| $\dot{P}$ (s s$^{-1}$) | $8.28(2) \times 10^{-12}$ | $8.06(4) \times 10^{-12}$ |
| $\ddot{P}$ (s s$^{-2}$) | $-7(2) \times 10^{-20}$ | $-7(2) \times 10^{-20}$ |
| $\tau_c$ (kyr) | 4.8 | 4.9 |
| $B$ (G) | $1.5 \times 10^{14}$ | $1.4 \times 10^{14}$ |
| $\dot{E}$ (erg s$^{-1}$) | $2.1 \times 10^{34}$ | $2.1 \times 10^{34}$ |

$a$Fully coherent timing solution.

Figure 1. Best-fitting residuals obtained using ephemeris A (top) and ephemeris B (bottom). Black: Swift/XRT; blue: RXTE/PCA; red: Chandra/ACIS-S; green: XMM–Newton/EPIC. Note that the last Chandra point of the upper panel (day ∼97) has not been included in the fit; its residual is shown with respect to the extrapolation of the ephemeris A. (See the electronic journal for a colour version of this figure.)

cross-correlation function was fit with a Gaussian. This yielded small phase lag values of $\Delta\phi = 0.020 \pm 0.008$ cycles between the Swift A and B profiles, 0.02 ± 0.01 cycles between the XMM–Newton A and B profiles and of 0.031 ± 0.004 cycles between the Chandra A and B profiles. The test confirms that indeed ephemeris B introduces only a mild correction with respect to ephemeris A. The pulsed fraction, estimated by fitting a sinusoidal curve to the data, was (93 ± 4) per cent, (88 ± 4) per cent, >94 per cent (1$\sigma$ lower limit) and (80 ± 16) per cent in the four Chandra observations in chronological order.

3.2 Burst analysis

We performed temporal and spectral analyses on the two triggered BAT events (Fig. 3). For the first event (trigger 458907, 2011 August 7 at 19:57:46.36 UT) we found $T_{90} = 11$ ms and a total duration of 12 ms. The values were computed by the BATTBLOCS task (based on a Bayesian blocks algorithm; Scargle 1998) from 15 to 150 keV mask-weighted light curves with 1 ms bin size.

We fit the time-averaged spectra with simple functions: power law, blackbody and optically thin thermal bremsstrahlung. They all provided statistically acceptable fits, but a blackbody model with $kT \sim 10$ keV yielded lower $\chi^2$ values in both cases (Table 3). For this model, the $T_{90}$ fluences of the bursts in the 15–150 keV band were $\sim 10^{-8}$ erg cm$^{-2}$ (first event) and $7 \times 10^{-9}$ erg cm$^{-2}$ (second event).
below 2 keV and above 10 keV were ignored, owing to the very few counts from Swift J1834.9–0846. The abundances used were those of Anders & Grevesse (1989) and photoelectric absorption cross-sections were from Balucinska-Church & McCammon (1992).

Although the relatively small number of photons (~800 net counts for observations 14329 and 14055 each, ~500 for observation 14056 and ~50 for observation 14057) allowed us to carry out only a limited spectral analysis, there was clear evidence for a rather soft spectrum and high absorption towards the source. Both a steep power law (photon index $\Gamma \sim 4$) and a blackbody with temperature $kT \sim 1$ keV gave acceptable fits. The best-fitting parameters for these spectral models are given in Table 4. No additional spectral components were statistically required. In general AXPs/SGRs, especially when in outburst, exhibit more complex (multicomponent) spectra, usually fit by the superposition of two blackbodies, or a blackbody (or a resonant cyclotron scattering model; Rea et al. 2008; Zane et al. 2009) and a high-energy power law (e.g. Mereghetti et al. 2005; Israel et al. 2007; Bernardini et al. 2009, 2011; Esposito et al. 2009; Rea et al. 2009). However, similarly to the case of SGR 1833–0832 (Esposito et al. 2011), the relatively low flux and high absorption of Swift J1834.9–0846 made our Chandra observations not very sensitive to the presence of additional spectral components.

During the time spanned by the first three Chandra observations, the spectrum softened and the X-ray flux decreased by ~30 per cent in the first two weeks, and then by a further ~60 per cent. To obtain flux measurements over the outburst, a blackbody model was fit to the Swift/XRT data simultaneously, with all parameters left free to vary except for the absorption column density, that was fixed at the Chandra value. This resulted in an acceptable fit ($\chi^2 = 0.91$ for 193 dof) with spectral parameters similar to those reported in Table 4 but much more poorly constrained. We plot the resulting long-term light curve in Fig. 4. The flux evolution could be satisfactorily described by a broken power law ($\chi^2 = 1.27$ for 16 dof, see Fig. 4). Fixing $t = 0$ at the time of the first burst, the break occurred at $(46 \pm 1) \text{ d}$, when the index changed from $\alpha_1 = 0.42 \pm 0.02$ to $\alpha_2 = 4.5 \pm 0.4$; the flux at the break time is $(1.11 \pm 0.3) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$. This result is in agreement with the trend reported in Kargaltsev et al. (2012), whose observations cover only the first part of the decay.

### 3.3 Spectral analysis of the X-ray persistent emission

For the spectroscopy (performed with the XSPEC 12.7 fitting package; Arnaud 1996) we concentrate on the Chandra spectra which, owing to the ACIS-S high throughput, the long observing time and the superb Chandra point spread function (PSF), are those with the best statistical quality and signal-to-noise ratio. We fit the spectra from the four 2011 observations simultaneously with the hydrogen column density tied between all data sets. Photons having energies

![Figure 3. Swift/BAT 15–150 keV mask-weighted light curve of the bursts observed from Swift J1834.9–0846 (bin size: 5 ms).](https://academic.oup.com/mnras/article-abstract/429/4/3123/1012968/Downloaded-from-https://academic.oup.com/mnras/article-abstract/429/4/3123/1012968)

### Table 3. Spectral analysis results for the bursts (Swift/BAT data).

| Trigger | Model | $kT$ (keV) | $\Gamma$ | Flux$^a$ (erg cm$^{-2}$ s$^{-1}$) | Red. $\chi^2$ (dof) |
|---------|-------|------------|----------|----------------------------|-----------------|
| 458907  | PL    | $3.1^{+0.2}_{-0.3}$ | $2.1 \times 10^{-7}$ | 1.22 (56) | |
| OTTB    | $29^{+1}_{-0.5}$ | $2.5 \times 10^{-7}$ | 1.00 (56) | |
| BB      | $9.3 \pm 0.8$ | $2.8 \times 10^{-7}$ | 0.82 (56) | |
| 501752  | PL    | $2.4^{+0.4}_{-0.3}$ | $6.5 \times 10^{-7}$ | 0.72 (56) | |
| OTTB    | $44^{+20}_{-12}$ | $6.4 \times 10^{-7}$ | 0.70 (56) | |
| BB      | $11 \pm 1$ | $6.1 \times 10^{-7}$ | 0.69 (56) | |

$^a$In the 15–150 keV energy range.

### 3.4 Diffuse emission

The diffuse emission reported by Kargaltsev et al. (2012) around Swift J1834.9–0846 for observation 14329 was clearly detected

### Table 4. Spectral analysis of the Chandra observations. Errors are at a 1σ confidence level.

| Obs. ID   | Model | $N_H$ (10$^{22}$ cm$^{-2}$) | $\Gamma$ | $kT$ (keV) | $R_{BB}$ (km) | Flux (obs./unabs.)$^b$ (10$^{-15}$ erg cm$^{-2}$ s$^{-1}$) | $\chi^2$/dof |
|-----------|-------|-----------------------------|----------|------------|--------------|-------------------------------------------------|-------------|
| Chandra/14329 | PL    | $3.8 \pm 0.3$               |          | $3.8 \pm 0.3$ | $1.9^{+0.1}_{-0.2}$ | $1.7 \pm 0.1$ | 0.77/117 |
| Chandra/14055 | PL    | $19.9 \pm 1.5$             |          | $4^{+0.4}_{-0.3}$ | $1.4 \pm 0.1$ | $0.51 \pm 0.3$ | |
| Chandra/14056 | BB    | $4.6 \pm 0.4$               |          | $6^{+1.8}_{-1.7}$ | $0.28^{+0.07}_{-0.11}$ | $0.17 \pm 0.4$ | |
| Chandra/14057 | PL    | $6^{+1.8}_{-1.7}$          |          | $10^{+0.7}_{-0.4}$ | $0.44^{+0.09}_{-0.07}$ | $0.12 \pm 0.3$ | |
| Chandra/14329 | BB    | $0.92 \pm 0.06$            |          | $0.83^{+0.05}_{-0.05}$ | $0.37^{+0.07}_{-0.06}$ | $0.47 \pm 0.3$ | |
| Chandra/14055 | BB    | $12.6^{+1.1}_{-1.0}$       |          | $0.6^{+0.2}_{-0.1}$ | $0.29^{+0.03}_{-0.1}$ | $0.027 \pm 0.05$ | |
| Chandra/14056 | BB    | $0.83^{+0.05}_{-0.05}$     |          | $0.83^{+0.05}_{-0.05}$ | $0.37^{+0.07}_{-0.06}$ | $0.47 \pm 0.3$ | |
| Chandra/14057 | BB    | $0.6^{+0.2}_{-0.1}$        |          | $0.6^{+0.2}_{-0.1}$ | $0.29^{+0.03}_{-0.1}$ | $0.027 \pm 0.05$ | |

$^a$The blackbody radius is calculated at infinity and for an arbitrary distance of 5.4 kpc.

$^b$In the 2–10 keV energy range.
also in the new Chandra observations. Considering the large absorption derived from the X-ray spectra, it was probably due to the scattering of the point source radiation by dust along the line of sight, as also observed in other magnetars (Rivera-Ingraham & van Kerkwijk 2010; Tiengo et al. 2010; Esposito et al. 2011; Olausen et al. 2011). The small field of view of the ACIS instrument used in 1/8 sub-array mode (width of 1 arcmin) allowed us to probe the inner part of the diffuse emission only. The more extended structure which Younes et al. (2012) interpreted as a magnetar wind nebula could not be investigated with these observations.

Owing to their longer path to the observer, the X-rays scattered by dust at a distance $d_{\text{dust}}$ are detected with a time delay which increases with the off-axis angle $\theta$ (in arcsec) according to

$$\Delta t = 1.4 \times 10^{-5} \frac{x d}{1 - x} \theta^2 \text{d},$$

where $d$ is the distance of the X-ray source (in kpc) and $x \equiv d_{\text{dust}}/d$ (Trümper & Schönfelder 1973). As a consequence, the halo photons detected in our Chandra observations (within ~30 arcsec from the central source) had a short time delay, less than 1 d (unless most of the dust is concentrated extremely close to Swift J1834.9–0846, say a few tens of pc). We then expect the ratio between the scattered and transmitted flux to be the same in all the Chandra observations.

For each Chandra observation, we extracted the spectra from three annuli around the point source, with radii of 2–10, 10–20 and 20–30 arcsec. The background spectrum was extracted from two 20–arcsec radius circles centred at more than 1 arcmin away from Swift J1834.9–0846. Based on ChART/MARX simulations of the Chandra PSF, we expect ~5, ~1 and ~0.5 per cent of the counts to come from the point source in the 2–10, 10–20 and 20–30 arcsec annuli, respectively. We estimated the halo flux by fitting the background-subtracted spectra with an absorbed power-law model to which we added a (fixed) blackbody component (parameters are those of the best fits in Table 4, with normalizations opportunely rescaled) to account for the small contamination from the point source estimated above. The resulting 2–10 keV fluxes of the two innermost annuli are plotted in Fig. 4; the spectra of the 20–30 arcsec region, owing to their poor count statistics, do not provide useful information and are not considered in the following.

As expected, the halo fluxes decreased with time. We performed the same analysis also on the Chandra pre-outburst observation (Obs. ID: 10126), obtaining 2–10 keV fluxes of $(1.0 \pm 0.3) \times 10^{-14}$ and $(2.4 \pm 0.9) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ for the diffuse emission in the 2–10 and 10–20 arcsec regions, respectively.

Since the observations were all carried out with the same detector and set-up, we could study the evolution in time of the relative contribution of the diffuse emission against the point source intensity by directly comparing the count rates in different regions. While the ratios between the net count rates of the halo in the two annuli and that of the point source remained constant (within the uncertainties) during the first three Chandra post-outburst observations, they significantly increased in the last one. This suggests the presence of an additional contribution to the fluxes of the diffuse emission. Indeed, if we subtract from each of the above count rates the net count rate observed in the same regions during the pre-outburst observation, the count rate ratios are consistent with being constant in time (see Fig. 5). This means that, if one assumes that the diffuse emission detected in the pre-outburst observation was present at the same level also in the most recent observations, the flux evolution of the diffuse emission detected after the outburst agrees with the expectations for a dust-scattering halo.

For a given model of scattered halo (consisting of a dust-scattering cross-section and of the assumed properties of the grains), the fractional halo intensity (as a function of the angle $\theta$ and the photon energy) depends on the amount of the dust along the line of sight and its spatial distribution. As discussed below, there is evidence that most of the dust in the direction of Swift J1834.9–0846 is concentrated in a few discrete clouds. We therefore consider for simplicity the case

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3 See http://cxc.harvard.edu/chart/index.html for details on the Chandra Ray Tracer (ChART) and Model of AXAF Response to X-rays (MARX) software packages.

4 In this case no contribution from the central source needed to be subtracted, since Swift J1834.9–0846 was not detected in this observation (see Kargaltsev et al. 2012 for a detailed analysis).
of a single cloud responsible for most (or all) of the observed scattered radiation. We use the dust cross-section in the Rayleigh–Gans approximation and a power-law distribution for the dimensions of the grains, with power-law index $q = −3.5$ and maximum and minimum grain size $a_{\text{max}} = 0.25 \mu\text{m}$ and $a_{\text{min}} = 0.005 \mu\text{m}$ (Mathis, Rumpl & Nordsieck 1977). Based on equation (1), we can neglect the time delay at the small angular radii we are considering.

To compare the predictions of this simple model with the data, we merged the first three post-outburst observations, which have the largest signal-to-noise ratio, and computed the halo-to-point-source ratios in the 2–10 and 10–20 arcsec regions and four energy bands in the 2–6 keV range. As done for the individual observations, the background and the diffuse emission in the pre-outburst observation were subtracted from the count rates of the different regions and the count ratios were corrected to account for the instrumental PSF. The observed ratios were fit with our halo model ($\chi^2 = 2.62$ for 6 dof, see Fig. 6), obtaining $x = d_{\text{halo}}/d = 0.963 \pm 0.004$ and a normalization corresponding to $N_{\text{H}} = (7.1 \pm 0.4) \times 10^{22} \text{ cm}^{-2}$ in the dust cloud, which is a significant fraction of the total hydrogen column density derived from the X-ray spectral analysis. Although an optimization of the dust model is beyond the scope of this work, we have checked that these results are not substantially affected by varying the dust-grain parameters within a reasonable range. In particular, we can robustly conclude that the dust cloud must be

![Figure 6](https://academic.oup.com/mnras/article-abstract/429/4/3123/1012968)

Figure 6. Ratio of the halo and point-source count rates in the sum of the first three post-outburst Chandra observations (black: 2–10 arcsec region; red: 10–20 arcsec region). The best-fitting dust-scattering halo model and its residuals (in standard deviation units) are indicated by the solid lines and filled squares, while the dotted lines and open squares correspond to the model and residuals obtained by fixing $x = d_{\text{halo}}/d = 0.9$. Assuming a distance of 5 kpc for Swift J1834.9–0846, the distance between the dust and the neutron star would be $185 \pm 20$ pc in our best-fitting model and 500 pc for $x = 0.9$. (See the electronic journal for a colour version of this figure.)

necessarily close to Swift J1834.9–0846 to generate the compact X-ray halo we observed with Chandra. In fact, as the $x$ parameter decreases, the halo counts in the 10–20 arcsec region progressively increase with respect to those in the inner region, indicating that the halo becomes significantly broader (as an example, see the best fit obtained by fixing $x = 0.9$ in Fig. 6).

4 RADIO OBSERVATIONS WITH THE GREEN BANK TELESCOPE

Radio observations of Swift J1834.9–0846 were taken at the Green Bank Radio telescope on 2011 August 18, 11 d after the first X-ray burst, and on three other occasions separated by ~1 month one from the other. Data were acquired at a central frequency of 2.0 GHz over a bandwidth of 800 MHz split into 512-MHz frequency channels, and 8-bit sampled every 655.36 µs. The duration of the first three observations (performed on August 18, September 20 and October 19) was 23 min while the last (on November 22) lasted 32 min.

About 100 MHz of the total bandwidth were affected by strong narrow-frequency radio interferences hence the interested frequency channels have not been considered in the analysis. After de-dispersing the signal over a wide range of dispersion measure (DM) values (0–3000 pc cm$^{-3}$), data were analysed both blindly, searching for significant peaks on the power spectra of the fast Fourier transformed time series, for single pulses on the time series directly, and by folding the de-dispersed data at the period obtained from X-ray observations. No signal was detected above a flux density of 0.05 mJy, which is the limit derived from the radiometer equation (see e.g. Manchester et al. 2001) for a signal-to-noise ratio of 10. This rather high ratio has been chosen for caution because the data (especially the last ones) were affected also by long-period, wide-band radio frequency interferences.

Also the three pointings of the Parkes Multi-beam Pulsar Survey (e.g. Manchester et al. 2001) closest to the source position were analysed in search of a pulsed (periodic or sporadic) signal. Nothing was found in any of the archival observations dating 1998 December 1, 1999 July 14 and 2003 October 18, down to a flux density limit of 0.22 mJy for the 1999 pointing (at 5 arcmin from the source) and 0.32 mJy for the two other pointings (at 7 arcmin from the source).

5 DISCUSSION

In this work we reported on the long-term evolution of the magnetar Swift J1834.9–0846 and its X-ray halo during the 2011 outburst using all available data from Chandra, XMM–Newton, Swift and RXTE. In particular, we presented three new observations obtained with the Chandra/ACIS-S instrument. The last observation was carried out on 2011 November 12, about 100 d after the onset of the bursting activity that had led to the discovery of the source. This long time-span enabled us to refine the rotational ephemeris available for the source. The extended monitoring of Swift J1834.9–0846 also revealed a monotonic decrease of the flux. The rate of change of the source luminosity varied in time. After a first phase during which the flux decreased following a rather shallow power law ($F \propto t^{-0.42}$ up to ~46 d from the onset), the decay became much faster, with $F \propto t^{-4.5}$. The trend we observed prior to the break is compatible with that reported in Kargaltsev et al. (2012), who, however, could not detect the change in slope because of the shorter time coverage of their observations.

The flux decay patterns observed in outbursting magnetars are quite diverse but can be grouped into three main classes:
The discovery of pulsed radio emission from a few transient magnetars (namely XTE J1810$−$197, 1E 1547$−$5408 and PSR 1622$−$4950; Camilo et al. 2006, 2007; Levin et al. 2010; Anderson et al. 2012) gave support to the possibility that magnetars and ordinary radio pulsars are linked at some level (see Perna & Pons 2011; Pons & Perna 2011 for theoretical work supporting this connection with respect to the outburst phenomenology). Indeed, Rea et al. (2012) recently suggested that magnetars radio emission, despite having peculiar characteristics, might be powered by the same physical mechanism responsible for the radio emission in ordinary pulsars. In particular, particle acceleration in a voltage gap, followed by a pair cascade, could be present also in the magnetosphere of a magnetar, the apparently different properties of the radio emission in the two classes of sources being possibly related to the twisted magnetic field of the magnetars. In this environment the pair cascade might in fact proceed differently, the radio emission be more variable and unstable and the radio spectrum be flatter due to the larger electron density that a twisted magnetosphere can sustain with respect to an ordinary pulsar.

Interestingly, the magnetars that showed radio pulsed emission so far were found to have rotational energy loss rates larger than their X-ray luminosity during quiescence (Rea et al. 2012). Assuming a distance of 5.4 kpc, the quiescent luminosity of Swift J1834.9$−$0846 is $L_X < 1.7 \times 10^{33}$ erg s$^{-1}$ (which corresponds to the flux limit derived from the archival Chandra observation by Kargaltsev et al. 2012). The rotational power is $\sim 2.1 \times 10^{33}$ erg s$^{-1}$ and the ratio $L_X/L_{\text{rot}} \sim 8 \times 10^{-4}$ is well below unity. This makes Swift J1834.9$−$0846 similar to the other radio emitting magnetars, hence it should be expected to show radio emission if the scenario by Rea et al. (2012) is correct. However, the non-detection of pulsed radio emission from Swift J1834.9$−$0846 could be due to unfavourable beaming, or, given the intermittent nature of the magnetar radio emission (e.g. Burgay et al. 2009), Swift J1834.9$−$0846 was simply not active at the time of our observations. We also note that, while our present limit for Swift J1834.9$−$0846 (1.5 mJy kpc$^{-2}$ for $d = 5.4$ kpc) is substantially lower than the observed radio luminosity of the known radio magnetars ($\sim 100$–400 mJy kpc$^{-2}$ at their peak; Camilo et al. 2006, 2007; Levin et al. 2010) it may be, however, non-entirely constraining, since more than one hundred ordinary radio pulsars have luminosity below this value.\textsuperscript{6} We thus cannot exclude that Swift J1834.9$−$0846 was active in radio but far less luminous than the known radio magnetars and too faint to be detected.

5.1 Diffuse emission

The four Chandra observations taken during the 2011 outburst decay of Swift J1834.9$−$0846 showed a significant decrease in the flux of the diffuse X-ray emission extending up to 20 arcsec from the neutron star. This variability strongly supports the dust-scattering halo origin already suggested by Kargaltsev et al. (2012). At such small angles, the ratio of the halo and point-source count rates is expected to be the same in all the observations, since the time delay of the halo photons is short enough to make the intrinsic variation of the source flux negligible (see equation 1 and Fig. 4). The data are consistent with such time-independent ratios, provided that the extended emission observed in 2009 (Kargaltsev et al. 2012) was present also during the 2011 outburst. We compared the energy and

\textsuperscript{6} See the online version of the Australia Telescope National Facility (ATNF) pulsar catalogue (Manchester et al. 2005) at http://www.atnf.csiro.au/research/pulsar/psrcat/
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spatial dependence of the fractional halo intensity with the predictions of a simple dust-scattering model, in which the dust has a power-law grain-size distribution and is concentrated in a single cloud. The narrow radial profile of the halo requires the dust cloud to be close to the SGR, at a fractional distance $x \approx 0.96$ (see Fig. 6).

The dust distribution along the line of sight can be estimated from radio observations of the $^{13}$CO ($J = 1 \rightarrow 0$) line (110.2 GHz), since this molecule is a good tracer of interstellar dust. We retrieved the data in the direction of Swift J1834.9–0846 from the high spatial resolution Boston University–Five College Radio Astronomical Observatory (BU–FCRAO) Galactic Ring Survey obtained with the FCRAO radio telescope (Jackson et al. 2006). The velocity-resolved line profile is shown in Fig. 8. No strong emission at radial velocities below 50 km s$^{-1}$, which for this direction correspond to distances <4 kpc, is visible. This exludes the presence of a significant amount of CO in the Local and Sagittarius spiral arms. The line profile shows prominent peaks at velocities compatible with the Scutum, Norma and 3-kpc arms. The highest peak in the line profile indicates that the largest CO concentration along this line of sight, using the Galactic rotational curve described in Sofue, Honma & Omodaka (2009), is located at $d \sim 5.2$ kpc in the Norma arm. Assuming that this dust cloud was the responsible for the scattering halo, the source would be located at a distance of $\sim 5.4$ kpc.

Although the sky coverage of the 2011 Chandra data was too small to include the X-ray diffuse emission extending to $\sim 2$–3 arcmin observed with XMM–Newton, our analysis provides some evidence that also this feature could be due to scattering by the same dust cloud responsible for the compact X-ray halo detected by Chandra. This interpretation would easily explain also the possible variability seen between the two XMM–Newton observations about 6 yr apart Younes et al. (2012). If confirmed by further observations, the variability of an extended feature $\sim 10$ light-years across (for $d \sim 5$ kpc) would be difficult to explain in the wind nebula interpretation, but compatible with a projection effect in a dust-scattering halo. The spatial asymmetry of the emission, which extended to the SW, can be explained by a non-uniform dust distribution in the plane of the sky. The CO sky maps of this region (Fig. 9), obtained selecting the CO data in the three velocity intervals shown in Fig. 8, show indeed a patchy structure. Although no clear correlation is visible between the CO maps and the X-ray surface brightness, the presence of large discontinuities on angular scales $< 1$ arcmin indicates an inhomogeneous dust distribution in clouds, over a spatial scale quite compatible with what implied by the observed asymmetry of the X-ray halo.

At variance with what we found for the emission within 20 arcsec from the source, at the arcmin scale the ratio of the diffuse to point-source emission had different values in the two XMM–Newton observations: the flux of Swift J1834.9–0846 in 2011 was $\sim 30$ times larger than in 2005, while the extended emission was brighter by only a factor of $\sim 2$ (see table 1 in Younes et al. 2012). This is not a problem in the dust-scattering interpretation because, for the distances we derived above ($d_{\text{dust}} \sim 5.2$ kpc, $d \sim 5.4$ kpc), angular distances between 50 and $\sim 200$ arcsec correspond to an
average time delay of ~1 month (see equation 1). Therefore, the halo photons detected in the 2011 XMM–Newton observation were emitted in the first days of the outburst (which started ~40 d earlier), when the source was brighter. As suggested by Younes et al. (2012) based on the non-detection of Swift J1834.9−0846 in the deep Chandra observation carried out in 2009, this SGR might have experienced an outburst shortly before the 2005 XMM–Newton observation. In the lack of direct observations of such a putative outburst, we assume it had the same flux evolution of the 2011 outburst (Fig. 4). Since the flux of Swift J1834.9−0846 in the 2005 observation (Younes et al. 2012) is similar to that measured in our last Chandra observation and the previous Chandra observation was executed ~40 d before, which approximately corresponds to the time delay expected for the large-scale diffuse emission, these photons were emitted when the source was ~15 times brighter. Therefore, this significantly larger flux can explain the different ratio between the halo and the point source flux observed in 2005 and in 2011. Note that such an explanation requires that the scattering dust is located close to the source, otherwise the time delay would be too small to account for the required difference in the fluxes. In conclusion, both the small- and large-scale X-ray haloes can be explained only if they are produced by dust close to Swift J1834.9−0846.

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REFERENCES

Anders E., Grevesse N., 1989, Geochimica Cosmochimica Acta, 53, 197
Anderson G. E. et al., 2012, ApJ, 751, 53
Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, ASP Conf. Ser. Vol. 101, Astronomical Data Analysis Software and Systems V. Astron. Soc. Pac., San Francisco, p. 17
Balucinska-Church M., McCammon D., 1992, ApJ, 400, 699
Barthelmy S. D. et al., 2005, Space Sci. Rev., 120, 143
Beloborodov A. M., 2009, A&A, 498, 195
Bernardini F. et al., 2009, A&A, 498, 195
Bernardini F. et al., 2011, A&A, 529, A19
Burgay M., Israel G. L., Possenti A., Rea N., Esposito P., Mereghetti S., Tiengo A., Götz D., 2009, Astron. Telegram, 1913
Burrows D. N. et al., 2005, Space Sci. Rev., 120, 165
Camilo F., Ransom S. M., Halpern J. P., Reynolds J., Helfand D. J., Zimermann N., Sarkissian J., 2006, Nat, 442, 892
Camilo F., Ransom S. M., Halpern J. P., Reynolds J., 2007, ApJ, 666, L93
D’Elia V. et al., 2011, GCN Circular, 12253
Esposito P. et al., 2009, ApJ, 690, L105
Esposito P. et al., 2010, MNRAS, 405, 1787
Esposito P. et al., 2011, MNRAS, 416, 205
Garmire G. P., Bautz M. W., Ford P. G., Nousek J. A., Ricker G. R., 2003, in Trümper J. E., Tananbaum H. D., eds, Proc. SPIE Vol. 4851, X-Ray and Gamma-Ray Telescopes and Instruments for Astronomy. SPIE, Bellingham, p. 28
Göküş E., Kouveliotou C., 2011, Astron. Telegram, 3542
Hoversten E. A. et al., 2011, GCN Circular, 12316
Israel G. L., Campana S., Dall’Oss S., Muno M. P., Cummings J., Perna R., Stella L., 2007, ApJ, 664, 448
Israel G. L. et al., 2008, ApJ, 685, 1114
Jackson J. M. et al., 2006, ApJ, 163, 145
Jahoda K., Markwardt C. B., Radeva Y., Rots A. H., Stark M. J., Swank J. H., Strohmayer T. E., Zhang W., 2006, ApJ, 163, 401
Kargaltsev O. et al., 2012, ApJ, 748, 26
Kuiper L., Hermsen W., 2011, Astron. Telegram, 3577
Levin L. et al., 2010, ApJ, 721, L33
Lytbarsky S., Eichler D., Thompson C., 2002, ApJ, 580, L69
Manchester R. N. et al., 2001, MNRAS, 328, 17
Manchester R. N., Hobbs G. B., Teoh A., Hobbs M., 2005, AJ, 129, 1993
Mathis J. S., Rumpl W., Nordsieck K. H., 1977, ApJ, 217, 425
Mereghetti S., 2008, A&AR, 15, 225
Mereghetti S. et al., 2005, ApJ, 628, 938
Misanovic Z., Kargaltsev O., Pavlov G. G., 2011, ApJ, 735, 33
Muno M. P., Gaensler B. M., Neuchit A., Miller J. M., Slane P. O., 2008, ApJ, 680, 639
Olusean S. A., Kaspi V. M., Ng C.-Y., Zhu W. W., Dib R., Gavriil F. P., Woods P. M., 2011, ApJ, 742, 4
Perna R., Pons J. A., 2011, ApJ, 727, L51
Pons J. A., Perna R., 2011, ApJ, 741, 123
Pons J. A., Rea N., 2012, ApJ, 750, L6
Rea N., Esposito P., 2011, in Torres D. F., Rea N., eds, Astrophysics and Space Science Proceedings, High-Energy Emission from Pulsars and Their Systems. Springer-Verlag, Berlin, p. 247
Rea N., Zane S., Turolla R., Lyutikov M., Götz D., 2008, ApJ, 686, 1245
Rea N. et al., 2009, MNRAS, 396, 2419
Rea N. et al., 2010, Sci, 330, 944
Rea N., Pons J. A., Torres D. F., Turolla R., 2012, ApJ, 748, L12
Rivera-Ingraham A., van Kerkwijk M. H., 2010, ApJ, 710, 797
Scargle J. D., 1998, ApJ, 504, 405
Sofue Y., Honma M., Omokada T., 2009, PASJ, 61, 227
Strüder L. et al., 2001, A&A, 365, L18
Thompson C., Duncan R. C., 1995, MNRAS, 275, 255
Thompson C., Duncan R. C., 1996, ApJ, 473, 322
Thompson C., Duncan R. C., 2001, ApJ, 561, 980
Thompson C., Lyutikov M., Kulkarni S. R., 2002, ApJ, 574, 332
Tiengo A. et al., 2010, ApJ, 710, 227
Trümper J., Schönfelder V., 1973, A&A, 25, 445
Turner M. J. L. et al., 2001, A&A, 365, L27
Turolla R., Zane S., Pons J. A., Esposito P., Rea N., 2011, ApJ, 740, 105
Vetri M., Stella L., Israel G. L., 2007, ApJ, 661, 1089
Younes G., Kouveliotou C., Kargaltsev O., Pavlov G. G., Göküş E., Wachter S., 2012, ApJ, 757, 39
Zane S., Rea N., Turolla R., Nobili L., 2009, MNRAS, 398, 1403

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