An anti-glitch in a magnetar

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Magnetars are neutron stars with X-ray and soft γ-ray outbursts thought to be powered by intense internal magnetic fields¹. Like conventional neutron stars in the form of radio pulsars, magnetars exhibit 'glitches' during which angular momentum is believed to be transferred between the solid outer crust and the superfluid component of the inner crust²⁻⁴. The several hundred observed glitches in radio pulsars⁵⁻⁷ and magnetars⁸ have involved a sudden spin-up (increase in the angular velocity) of the star, presumably because the interior superfluid was rotating faster than the crust. Here we report X-ray timing observations of the magnetar 1E 2259+586 (ref. 8), which exhibited a clear ‘anti-glitch’—a sudden spin-down. We show that this event, like some previous magnetar spin-up glitches⁸, was accompanied by multiple X-ray radiative changes and a significant spin-down rate change. Such behaviour is not predicted by models of neutron star spin-down and, if of internal origin, is suggestive of differential rotation in the magnetar, supporting the need for a rethinking of glitch theory for all neutron stars⁹⁻¹¹.

1E 2259+586 is a magnetar with a rotation period of about 7 s, with a spin-inferred surface dipolar magnetic field strength of 5.9 × 10¹³ G. Over 16 years of monitoring with the Rossi X-ray Timing Explorer, 1E 2259+586 has shown a very stable spin-down rate and pulsed flux, with the exception of two spin-up glitches in 2002 (ref. ⁹) and 2007 (ref. ¹²), and a small timing event in 2009 (ref. ¹²). The 2002 glitch was also accompanied by an increase in X-ray luminosity by a factor of 20 (ref. ⁹) and X-ray bursts¹³, neither of which was seen in the 2007 glitch.

We began monitoring 1E 2259+586 with NASA’s Swift X-ray Telescope¹⁴ in July 2011. Observations were made every 2–3 weeks, with typical exposure times of 4 ks. From each observation, we obtained a pulse time-of-arrival (TOA) by folding the X-ray time series at the current pulse period and aligning this folded light curve with a high signal-to-noise template.

We fitted the pulse TOAs to a long-term timing model that keeps track of every rotation of the neutron star. This model predicts when the pulses should arrive at Earth, taking into account the pulsar rotation as well as astrometric terms. We compared the observed TOAs with the model predictions, and obtained best-fit parameters by χ² minimization, using the TEMPO2¹⁵ software package. Until the observation on 14 April 2012 (modified Julian date, MJD 56,031.18), these TOAs were well fitted using only a frequency and first frequency derivative, as shown in Fig. 1.

The subsequent data, however, clearly were not predicted by this simple model. TOAs starting on 28 April 2012 (MJD 56,045.01) showed an apparently instantaneous change of the frequency—which we dub an ‘anti-glitch’. On 21 April 2012 (MJD 56,038), consistent with the epoch of this sudden spin-down, a 36-ms hard X-ray burst was detected by the Fermi Gamma-ray Burst Monitor¹⁶, with a fluence of about 6 × 10⁻⁸ erg cm⁻² in the 10–1,000 keV range. No untriggered bursts from the Gamma-ray Burst Monitor were seen within three days of the observed burst¹⁶. Also, on 28 April 2012 (MJD 56,045.01), coincident with the nearest post-anti-glitch observation, we detected an increase in the 2–10-keV flux by a factor of 2.00 ± 0.09 fitting only for the pre-anti-glitch timing solution. The inset shows the same timing residuals, zooming in on the anti-glitch epoch.

![Figure 1](https://example.com/figure1.png)

**Figure 1** | Timing and flux properties of 1E 2259+586 around the 2012 event. a, 1E 2259+586’s spin frequency as a function of time, determined by short-term fitting of (typically) five TOAs. The grey horizontal error bars indicate the ranges of dates used to fit the frequency, and the vertical error bars (generally smaller than the points) are standard 1σ uncertainties. The red and blue solid lines in a represent the fits to the pulse TOAs, as displayed in Table 1, with red representing model 1, and blue model 2. b, Timing residuals (differences between the initial model and observed data) of 1E 2259+586 after fitting only for the pre-anti-glitch timing solution. The inset shows the same timing residuals, zooming in on the anti-glitch epoch. c. The absorbed 2–10-keV X-ray flux. The error bars indicate the 1σ uncertainties, and the green line is the best-fit power-law decay curve with an index of −0.38 ± 0.04. The dashed vertical lines running through all panels indicate the glitch epochs, the black line being the anti-glitch, and blue and red lines the second event in the models shown in Table 1. The timing residuals for these fits can be seen in the Supplementary Information.

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Sudden spin-down glitches have not previously been observationally demonstrated, though some magnetar events have been suggestive. A spin-down in magnetar SGR 1900+14 (ref. 17) occurred during an 80-day gap in the source monitoring, but could have been a gradual slowdown, as was also possible for the 2009 timing event in 1E 2259+586 (ref. 12). Net spin-downs have been seen in magnetar 4U 0142+61 (ref. 18) and in the high-magnetic-field-rotation-powered pulsar PSR J1846–0258 (ref. 19) but were due to spin-up glitch over-recoveries on timescales of 17 and 127 days, respectively. If the 1E 2259+586 event were due to a spin-up glitch and subsequent over-recovery, we place a 3σ upper limit on the recovery decay time of 3.9 days for a spin-up of size $\Delta \nu / \nu = 1 \times 10^{-6}$. Even for an infinitesimally small spin-up glitch, the decay time was less than 6.6 days, far shorter than any previously observed magnetar recovery timescales.

Following the detection of the anti-glitch, we looked for evidence of particle outflow, proposed as a possible mechanism for the apparent spin-down in SGR 1900+14 (ref. 20). We carried out radio imaging on 21 August 2012 using the Expanded Very Large Array (New Mexico, USA) in the B-array configuration with a 240-min integration time. This yielded images with effective angular resolution of 1.2″. We performed standard flagging, calibration and imaging using the Common Astronomy Software Applications (CASA) package21. No source was found at the position of 1E 2259+586, and we place a 3σ flux density limit of 7.2 μJy at 7 GHz for a point source. This is significantly lower than the previous upper limit of 50 μJy at 1.4 GHz (ref. 9). If a putative outflow were expanding at 0.7c (where c is the velocity of light in a vacuum), as was the case for a radio outflow from SGR 1806–20 (ref. 22) at the time of its outburst, we would expect a nebular radius of 4″. For this radius, we obtain a 3σ flux density limit of 0.46 mJy. The limit is more stringent if the size is smaller, and reduces to 7.2 μJy if unresolved.

In X-rays, we also detected no evidence for such outflow in a 10-ks Chandra High Resolution Camera (HRC)-I image taken on 21 August 2012. Using simulations, we place an upper limit on X-ray flux from a putative outflow at 2% of the total 1–10-keV X-ray emission of the magnetar, for a 4″ circular nebula with a Crab-like spectrum.

There are two main possibilities for the origin of the anti-glitch: either an internal or external mechanism, as follows. An impulse-like angular-momentum transfer between regions of more slowly spinning superfluid and the crust could be the source of the anti-glitch20. A slower angular-momentum transfer to such a region or the decoupling of a significant amount of the moment of inertia of the star could account for the enhanced spin-down rate. The second event, either glitch or anti-glitch, can similarly be modelled by angular-momentum transfers from differentially rotating regions of the neutron star superfluid. The radiatively quiet nature of the second event does not pose a problem for the internal model because many glitches are observed to be radiatively silent. The behaviour indicated by an impulsive anti-glitch offers new evidence for possible significant internal structural changes and differential rotation in magnetars at glitch epochs.

An external model such as an outflow along the open field lines of the magnetosphere20,23–25, or a sudden twisting of the field lines26, could be the cause of the anomalous spin-down behaviour. However, in a wind model, the second timing event should also be accompanied by a radiative change, like the first one. If this behaviour was caused by twisting magnetic field lines, it should be followed by a gradual untwisting and a similar behaviour reflected in $\nu$ (ref. 26; see Supplementary Information). We suggest that this magnetar anti-glitch, X-ray outburst, and subsequent evolution indicate the need for a rethinking of glitch theory for all neutron stars20,11.

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Table 1 | Timing parameters for 1E 2259+586

| Parameter | Value |
|-----------|-------|
| Observation dates | 23 July 2011 to 1 January 2013 |
| Dates (MJD) | 55,765,829 to 56,293,332 |
| Epoch (MJD) | 55,380,000 |
| Number of TOAs | 51 |
| $\nu$ (s$^{-1}$) | 0.143, 285, 110(4) |
| $\nu$ (s$^{-2}$) | $-9.80(9) \times 10^{-15}$ |
| Glitch epoch 1 (MJD) | 56,035(2) |
| $\Delta \nu_1$ (s$^{-1}$) | $-4.5(6) \times 10^{-8}$ |
| $\Delta \nu_2$ (s$^{-2}$) | $-2.7(2) \times 10^{-14}$ |
| Glitch epoch 2 (MJD) | 56,125(2) |
| $\Delta \nu_1$ (s$^{-1}$) | $3.6(7) \times 10^{-8}$ |
| $\Delta \nu_2$ (s$^{-2}$) | $2.6(2) \times 10^{-14}$ |
| Root-mean-square residuals (ms) | 56.3 |
| $\chi^2/\nu$ | 45.4/44 |

Model 1

| Glitch epoch 1 (MJD) | 56,035(2) |
| $\Delta \nu_1$ (s$^{-1}$) | $-9(1) \times 10^{-8}$ |
| $\Delta \nu_2$ (s$^{-2}$) | $1.3(4) \times 10^{-14}$ |
| Glitch epoch 2 (MJD) | 56,090(2) |
| $\Delta \nu_1$ (s$^{-1}$) | $-6.8(8) \times 10^{-8}$ |
| $\Delta \nu_2$ (s$^{-2}$) | $1.1(4) \times 10^{-14}$ |
| Root-mean-square residuals (ms) | 51.5 |
| $\chi^2/\nu$ | 38.1/44 |

Numbers in parentheses are TEMPO2-reported 1σ uncertainties.
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Author Contributions R.F.A. performed the data analysis and wrote portions of the analysis software. V.M.K. designed the study, was the project leader for the Swift data, proposed for the Chandra data and assisted with the interpretation of the data analysis and the theoretical implications. C.Y.N. proposed for the VLA data and reduced them and the Chandra data. K.N.G. and D.T. assisted with the theoretical implications. P.S. wrote significant portions of the Swift analysis software. A.P.B., N.G. and J.A.K. assisted with Swift observations and data analysis. R.F.A. wrote the paper with guidance from V.M.K. and with significant input from all co-authors.

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