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1 Observations

The *Swift* X-Ray Telescope (XRT) is a Wolter-I telescope with an *XMM-Newton* EPIC-MOS CCD22 detector, sensitive in the 0.5 -10 keV range. The XRT was operated in Windowed-Timing (WT) mode for all observations, which gives 1.76-ms time resolution. *Swift* observations of 1E 2259+586 had typical exposure times of 4 ks.

The X-ray flux was measured by processing level 1 data products which were obtained from the HEASARC *Swift* archive, reduced using the *xrtpipeline* standard reduction script, and barycentred to the position of 1E 2259+586 ($RA = 23^h01^m07.900^s, DEC = 58°52'46.00''$), using HEASOFT $v6.12$ and the *Swift* 20120209 CALDB. A 40-pixel long region centred on the source was extracted, as well as a background region of the same size located away from the source. To investigate the flux and spectral behaviour of 1E 2259+586, spectra were extracted from the selected regions using *xselect*, and fit to an N_H-absorbed blackbody and power-law model using *XSPEC* package version 12.7.0q[27]. N_H was fixed at the value of $0.97 \pm 0.03 \times 10^{22}$ cm^{-2}, determined by co-fitting all the pre-glitch spectra. The spectra were grouped with a minimum of 20 counts per energy bin. Ancillary response files were created using the FTOOLS *xrtmkarf* and the standard spectral redistribution matrices.

2 Discussion

The physical cause of the glitching behaviour of the magnetar and the enhanced spin down can be due to either internal or external mechanisms.

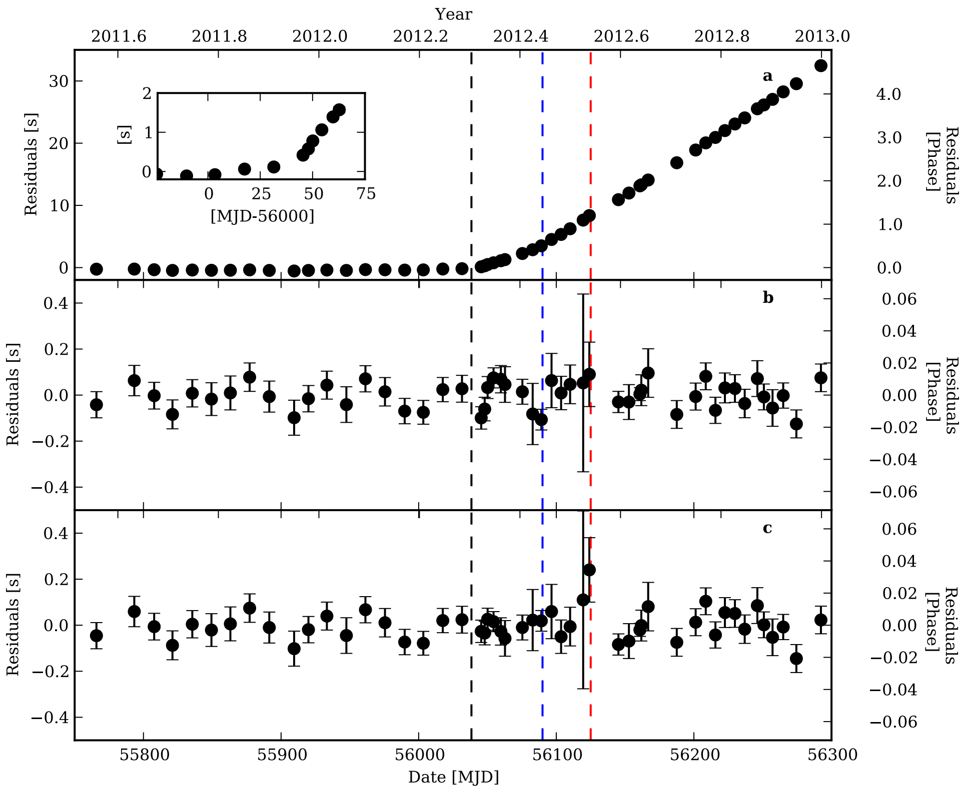
In regular pulsars, we expect the crust to spin slower than the uniformly rotating superfluid. However, in a magnetar, there is significant internal free energy generated by the magnetic-field decay[1], which could potentially drive differential rotation. Such differential rotation could allow for regions of superfluid to be spinning slower than the crust. An impulse-like angular momentum transfer between such regions and the crust could be the source of the anti-glitch, while a slower angular momentum transfer to such a region could account for the enhanced by a factor of either ~ 4 or ~ 2 spin-down rate. Another possible cause of the enhancement in the spin-down rate is by decoupling $\sim 3/4$ or $\sim 1/2$, respectively, of the moment of inertia on which the torque is acting[9]. In a normal pulsar glitch, $\sim 1\%$ of the moment of inertia is required to explain the observed $\Delta\dot{\nu}/\nu$ of about 0.01. Recent studies[11,28] suggest that even in normal pulsars, the crustal superfluid does not provide sufficient angular momentum for glitches, and a larger reservoir is needed. The extreme fields in magnetars could mediate the coupling of the crust and superfluid in the outer core. Events that release energy to the outside in the form of bursts should also alter the internal dynamics, leading to changes in the coupling and eventually to the moment of inertia. The exchange of energy between the core and the crust can heat the latter and enhance the X-ray luminosity[29].

Another internal mechanism that has been proposed in the context of SGR 1900+14[20] is the twisting of a patch of crust by a magnetospheric event which could cause a change in the angular momentum of the superfluid by the net motion of pinned vortices. Such a mechanism would typically cause a net spin up of the crust for a uniformly rotating superfluid. In this model, a slow plastic twist resulting in a sudden unpinning event could cause an anti-glitch. However, such a slow plastic deformation would be accompanied by a small relative decrease in the spin-down rate prior to the anti-glitch, which was not observed.

An external mechanism which varies the torque could also have caused the observed spin-down behaviour. An outflow along the open field lines of the magnetosphere could provide an additional torque which would increase the spin down by a factor of $\sim 2 - 4$. This would require a wind of luminosity $\sim 1.5 \times 10^{33}$ erg s^{-1} to act for a week, to explain the initial anti-glitch and to be followed by a $\sim 1 \times 10^{32}$ erg s^{-1} wind to cause the enhanced spin-down. In the two anti-glitch model, it would conclude with a rejuvenated flux to explain the increased torque at the time of the second anti-glitch. While the levels of X-ray luminosity due to the enhanced spin down would be undetectable in our monitoring, that from the short-term strong winds needed to explain the anti-glitches would have been. While we cannot exclude this model, it has low predictive power. Similarly, a sudden twisting of the field lines, through internal magnetic evolution, or external field activity, during the initial event can lead to larger torques. The twist needed to achieve this torque is ~ 3 rad if the displacement is confined in the polar cap or in a ring in that region,[25] and ~ 1 rad for a global twist[30]. However, if the currents supporting the twisted field dissipate smoothly following the initial twist, then $\dot{\nu}$ should also follow this trend. In this model the second anti-glitch requires a similar process. While a clear X-ray outburst and profile change were detected coincident with the first anti-glitch, there was no significant increase in X-ray luminosity, nor significant pulse profile changes coinciding with the second anti-glitch, even though the two events would have been similar in magnitude.

Determining whether the observed anti-glitch had origin internal or external to the star clearly has potential importance for our understanding of neutron-star structure. This could be accomplished in principle by, for example, better constraining the time scale on which the anti-glitch occurs, since an internal angular momentum transfer is likely to yield a near-instantaneous event, where as magnetospheric twists should have a longer evolution time scale. A sensitive all-sky X-ray monitor would be useful in this regard.

Supplementary Figure 1: Timing residuals for 1E 2259+586. Panels **a**, **b**, and **c** show timing residuals, the difference between the predicted and measured TOAs for the timing models shown in Table 1. Panel **a** takes into account only the long-term pre-anti-glitch timing model, with the inset showing the phase jump and significant slope change that indicates the anti-glitch. Panel **b** shows these residuals after fitting Model 1, the anti-glitch and the glitch, and Panel **c** for Model 2, the two anti-glitch model. The dashed vertical lines indicate glitch epochs – the black line the common anti-glitch epoch, the red line the glitch epoch in model 1, and the blue the second anti-glitch epoch in model 2.



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