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A variable absorption feature in the X-ray spectrum of a magnetar

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Soft-γ-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are slowly rotating, isolated neutron stars that sporadically undergo episodes of long-term flux enhancement (outbursts) generally accompanied by the emission of short bursts of hard X-rays[1,2]. This behaviour can be understood in the magnetar model[3–5], according to which these sources are mainly powered by their own magnetic energy. This is supported by the fact that the magnetic fields inferred from several observed properties[6–8] of SGRs and AXPs are greater than—or at the high end of the range of—those of radio pulsars. In the peculiar case of SGR 0418+5729, a weak dipole magnetic moment is derived from its timing parameters[9], whereas a strong field has been proposed to reside in the stellar interior[10,11] and in multipole components on the surface[12]. Here we show that the X-ray spectrum of SGR 0418+5729 has an absorption line, the properties of which depend strongly on the star's rotational phase. This line is interpreted as a proton cyclotron feature and its energy implies a magnetic field ranging from 2×10^{14} gauss to more than 10^{15} gauss.

On 2009 June 5 two short bursts of hard X-rays, detected by Fermi and other satellites, revealed the previously unknown source SGR 0418+5729[13]. Subsequent observations with the Rossi X-ray Timing Explorer (RXTE), Swift, Chandra and X-ray Multi-mirror Mission (XMM) Newton satellites found the new SGR to be an X-ray pulsar with a period of ~9.1 s and a luminosity of $\sim 1.6 \times 10^{34}$ erg s^{-1} (in the 0.5–10 keV band and for a distance of 2 kpc)[13,14]. During the three years after the onset of the outburst, the spectrum softened and the luminosity declined by three orders of magnitude, but remained still too high to be powered by rotational energy[9,10,14]. The measured spin-down rate of 4×10^{-15} s s^{-1} translates (under the assumption of a rotating magnetic dipole *in vacuo*) into a magnetic field $B = 6 \times 10^{12}$ G at the magnetic equator[9], a value well in the range of normal radio pulsars. However, the presence of high-order multipolar field components of 10^{14} G close to the surface has been invoked to interpret the spectrum of the source in the framework of atmosphere models[12]. In any case, a strong crustal magnetic field ($>10^{14}$ G) seems to be required to explain the overall properties of SGR 0418+5729 within the magnetar model[9,11].

Hints of the presence of an absorption feature at 2 keV in the spectrum of SGR 0418+5729 were found in the phase-resolved analysis of data (with relatively low-count statistics) from the Swift X-ray Telescope (XRT) taken during 2009 July 12–16[14]. Thanks to the large collecting area and good spectral resolution of the European Photon Imaging Camera (EPIC), we were able to perform a more detailed investigation using data collected by XMM-Newton during a 67-ks long observation performed on 2009 August 12, when the source flux was still high (5×10^{-12} erg cm^{-2} s^{-1} in the 2–10 keV band).

To examine the spectral variations as a function of the star's rotational phase without making assumptions about the X-ray spectral energy distribution of SGR 0418+5729, we produced a phase–energy image by binning the EPIC source counts into energy and rotational phase channels and then normalizing to the phase-averaged energy spectrum and pulse profile. The normalized phase–energy image (Fig. 1) shows a prominent V-shaped feature in the phase interval ~0.1–0.3. This is produced by a lack of counts in a narrow energy range with respect to nearby energy channels, that is, an absorption feature at a phase-dependent energy. The regular shape of the feature in the phase–energy plane as well as its presence in the three independent EPIC detectors (see Supplementary Fig. 5) exclude the possibility that it results from statistical fluctuations in the number of counts or from an instrumental effect. Another absorption feature is visible at low energies at phase ~0.5–0.6.

We extracted from the EPIC data the phase-averaged spectrum of SGR 0418+5729, as well as the spectra from 50 phase intervals of width 0.02 rotational cycles, as described in the Supplementary Information. The phase-averaged spectrum can be adequately fitted by either a two-blackbody model ($\chi^2_\nu = 1.198$ for 196 degrees of freedom, d.f.) or a blackbody plus power-law model ($\chi^2_\nu = 1.105$ for 196 d.f.), corrected for interstellar absorption (see refs 11 and 12 for other models that can fit the spectrum).

The 15 spectra extracted from the phase intervals 0.1–0.3 and 0.5–0.6, unlike those of the remaining phases, cannot be fitted by a renormalization of the phase-averaged best-fit model, which gives in most cases null hypothesis probabilities in the range 10^{-4}–10^{-9} (see Supplementary Fig. 4). They are instead well fitted (null hypothesis probability >0.03) by the addition of a narrow absorption line component, which can be equally well modelled with a Gaussian profile or a cyclotron absorption line model[15] (the improvement obtained by adding a cyclotron component in the phase intervals 0.1–0.3 and 0.5–0.6 can be seen in Supplementary Fig. 4). The best-fit line parameters as a function of phase are shown in Fig. 2 and an example of a phase-resolved spectrum is displayed in Fig. 3.

We searched for the phase-dependent absorption feature in all the available X-ray observations of SGR 0418+5729 and found that it was present in the phase interval 0–0.3, and up to higher energies than in XMM-Newton, in RXTE data taken during the first two months of the outburst (see Supplementary Fig. 6).

Absorption features have been observed in the X-ray spectra of various classes of neutron stars[16–23] and interpreted as being due to either cyclotron absorption (by electrons or protons) or bound–bound atomic transitions. However, variations in the line energy as a function of the rotational phase as large as in SGR 0418+5729 (by a factor of ~5 in one-tenth of a cycle) have not been seen in any source.

In a neutron star atmosphere, different atomic transitions might be responsible for a phase-variable absorption feature if temperature, elemental abundance or magnetic field vary strongly on the surface. The line energies observed in SGR 0418+5729 (~1–5 keV) rule out transitions in magnetized H and He, which occur below ~1 keV (refs 24, 25). On the other hand, the absorption spectra of heavier elements are much more complex (see, for example, ref. 26 for C, O and Ne) and some lines

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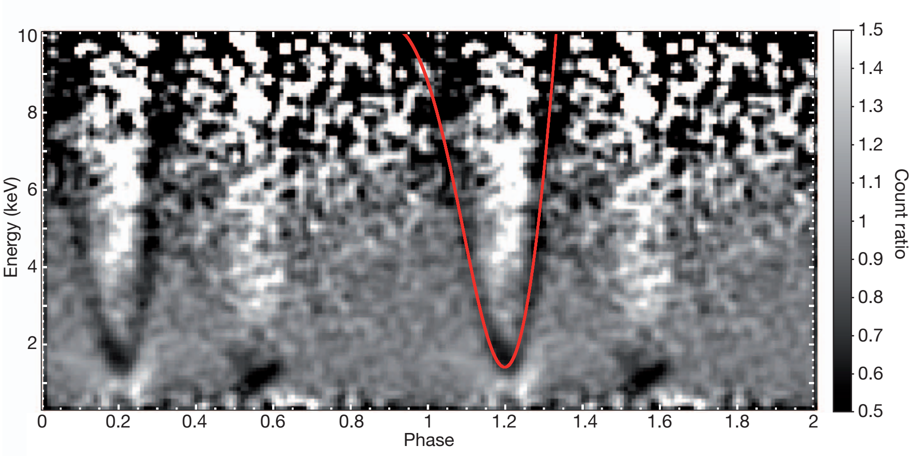

Figure 1 | Phase-dependent spectral feature in the EPIC data of SGR 0418+5729. Normalized energy versus phase image obtained by binning the EPIC source counts into 100 phase bins and 100-eV-wide energy channels and dividing these values first by the average number of counts in the same energy bin (corresponding to the phase-averaged energy spectrum) and then by the relative 0.3–10 keV count rate in the same phase interval (corresponding to the pulse profile normalized to the average count rate). The red line shows (for only one of the two displayed cycles) the results of a simple proton cyclotron model consisting of a baryon-loaded plasma loop emerging from the surface of a magnetar and intercepting the X-ray radiation from a small hotspot (see Supplementary Fig. 7 and Supplementary Table 1).

could occur at high enough energies. However, to explain the phase resolved spectra of SGR 0418+5729, the physical conditions of a heavy-element atmosphere are forced to vary in such a way that a single transition should dominate the opacity at each of the phases where the absorption line is detected.

A more straightforward explanation for the line variability can instead be given if the feature is due to cyclotron resonant scattering.

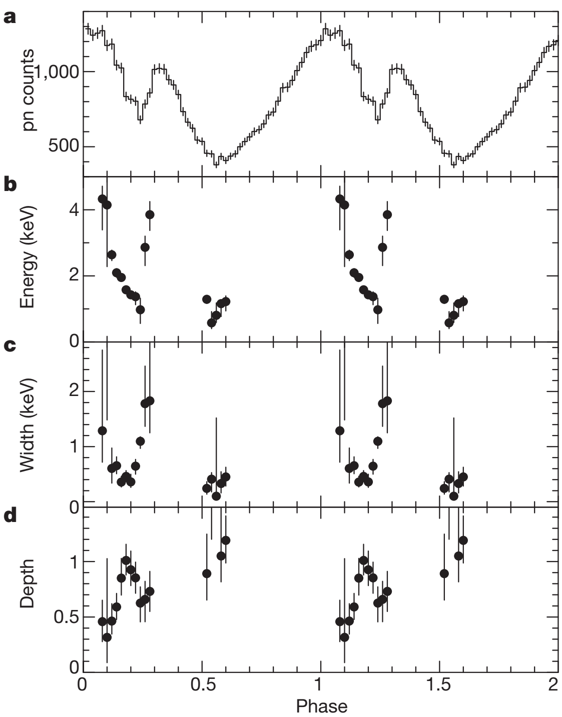

Figure 2 | Results of the phase-resolved spectroscopy of SGR 0418+5729. **a**, Pulse profile obtained by folding the 0.3–10 keV EPIC positive–negative junction (pn) detector light curve at the neutron star spin period $P = 9.07838827$ s. The data points are the number of counts in each phase-dependent spectrum. **b–d**, Line energy (E_c; **b**), width (W; **c**) and depth (D; **d**) of the cyclotron feature as a function of the spin phase. The model consists of a blackbody plus a power law and an absorption line, modified for the interstellar absorption (see Supplementary Information). For the line we used the cyclotron absorption model from ref. 15: $F(E) = \exp\left(-D\frac{(WE/E_c)^2}{(E-E_c)^2+W^2}\right)$. The interstellar absorption, temperature, photon index and relative normalizations of the two components were fixed to the best-fit values of the phase-integrated spectrum: $N_H = (9.6 \pm 0.5) \times 10^{21}$ cm^{-2}, $kT = 913 \pm 8$ eV, $\Gamma = 2.8 \pm 0.2$, $(R_{BB}/d)^2 = 0.81 \pm 0.03$ km^2 kpc^{-2} and $K_{PL} = (1.5 \pm 0.2) \times 10^{-3}$ photons cm^{-2} s^{-1} keV^{-1} at 1 keV. Vertical error bars, 1s.d.

The cyclotron energy (in keV) for a particle of charge e and mass m in magnetic field B (in gauss) is given by

$$E_B \approx \frac{11.6}{1+z}\left(\frac{m_e}{m}\right)\left(\frac{B}{10^{12}}\right)$$

where $(1+z)^{-1} = [1 - 2GM_{NS}/(Rc^2)]^{1/2}$ (which is ~0.8 at the star surface for typical neutron star mass and radius $M_{NS} = 1.4M_\odot$ and $R_{NS} = 12$ km, respectively) accounts for the gravitational redshift at distance R from the neutron star centre, m_e is the mass of the electron, and c is the velocity of light. In this case, the phase variability of the feature energy would simply be due to the different fields experienced by the charged particles interacting with the photons directed towards us as the neutron star rotates.

If the absorbers and scatterers are electrons hovering near the star surface, the expected line energy is ~70 keV for the dipole field at the equator of SGR 0418+5729 ($B = 6 \times 10^{12}$ G); this line energy is more than 10 times higher than that observed. A possible way to explain this large discrepancy might be to assume that the electrons producing the line are located higher up in the magnetosphere in a dipolar geometry, where the magnetic field is smaller ($R \approx 3R_{NS}$ to have $E_B \approx 2$ keV). Moreover, such an electron population should also be nearly mono-energetic, or subrelativistic, in order to prevent Compton scattering from washing out the feature, which would require a mechanism to maintain slowly moving electrons confined in a small volume high in the magnetosphere.

If the particles responsible for the cyclotron scattering are protons, the energy range of the SGR 0418+5729 spectral feature requires a magnetic field $>2 \times 10^{14}$ G (it would be even larger for heavier ions). In the framework of the magnetar model, the unprecedented phase-variability of the line energy can be explained by the complex topology of magnetar magnetospheres, in which global and/or localized twists play an important part[5]. This is particularly true for SGR 0418+5729, which has a weak dipolar component, as testified by the small spin-down value, whereas a much stronger internal magnetic field has been advocated to explain its X-ray luminosity and burst activity[10,11]. Furthermore, the presence of small-scale, strong, multipolar components of the surface field has been inferred by fitting its phase-averaged X-ray spectrum with models of magnetized neutron star atmospheres[12].

In this context, the observed line variability might be due to the presence of either strong magnetic field gradients along the surface or vertical structures (with a spatially dependent field) emerging from the surface. To work out how the dynamic magnetosphere of a magnetar should look, an analogy with the solar corona in the proximity of sunspots has been proposed (see, for example, ref. 27). In particular, localized, baryon-rich magnetic structures (in the form of rising flux tubes) or 'prominences' (produced by magnetic reconnection or the emergence of the internal field near a crustal fault) have been proposed to explain some of the observed properties of the giant flare emitted

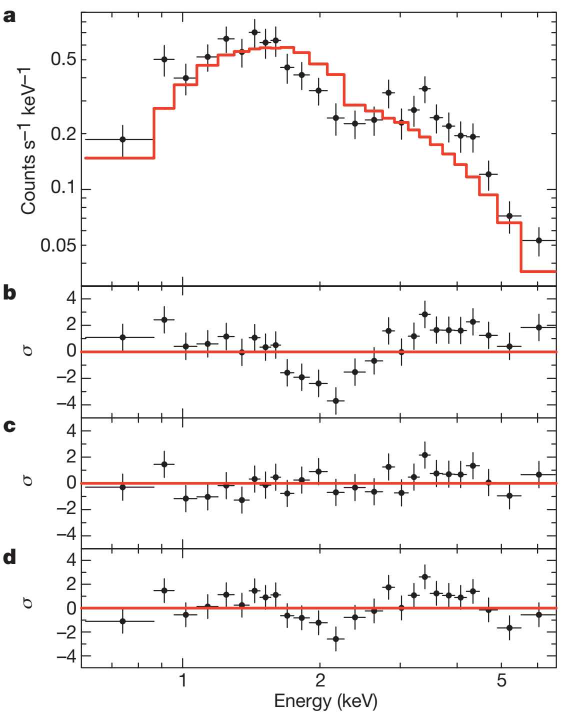

Figure 3 | Example of a phase-resolved EPIC pn spectrum and its residuals with respect to different models. **a**, Spectrum from the phase interval 0.15–0.17 (black dots) and best-fit model of the phase-averaged spectrum, rescaled with a free normalization factor (red line). **b**, Residuals with respect to this model ($\chi^2_\nu = 2.75$ for 25 d.f.); **c**, residuals after the addition of an absorption line (cyclabs model in XSPEC, with parameters as in Fig. 2; $\chi^2_\nu = 0.94$ for 22 d.f.); **d**, residuals with respect to an absorbed blackbody plus power-law model with free temperature, photon index and normalizations ($kT = 1.11 \pm 0.06$ keV and $\Gamma = 3.8 \pm 0.4$; $\chi^2_\nu = 1.75$ for 22 d.f.). This is one of the models (with the same number of free parameters) that we also explored to fit the phase-resolved spectra. In this case, we obtained fits of comparable quality to those with the line model at most phases, but worse fits in the phase interval 0.11–0.21. A joint fit to these five spectra gave an unacceptable χ^2_ν of 1.56 for 116 d.f., to be compared with χ^2_ν of 1.08 for the absorption line model (same number of d.f.). Horizontal error bars indicate the energy channel width; vertical error bars, 1s.d.; residuals σ are in units of standard deviations.

in 2004 by SGR 1806–20[28,29]. If a similar scenario, albeit on a reduced scale, occurred during the outburst of SGR 0418+5729, a spectral feature might arise as thermal photons from the hotspot (a small hot region on the neutron star surface, responsible for most of the X-ray emission, which could be itself related to the prominence) cross the plasma threading the magnetic loop. A proton density $\sim 10^{17}$ cm^{-3} is needed to produce a resonant scattering depth of order unity[5]. Protons, being heavy, do not rise much above the surface and move subrelativistically[5], so resonant scattering in the prominence is likely to produce a narrow feature instead of an extended tail. As the star rotates, photons emitted in different directions pass through portions of the prominence with different magnetic field, density and size, giving rise to the observed variations of the line centroid and width. A simple quantitative model based on this picture is presented in Supplementary Information. Results, obtained with a geometry consistent with the constraints derived from the X-ray pulsed fraction of SGR 0418+5729, are in good agreement with the observed variations of the feature with phase (Fig. 1).

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