A low-magnetic-field Soft Gamma Repeater

N. Rea[1*], P. Esposito[2], R. Turolla[3,4], G. L. Israel[5],
S. Zane[4], L. Stella [5], S. Mereghetti[6], A. Tiengo[6],
D. Götz[7], E. Göğüş[8], C. Kouveliotou[9]

[1]Institut de Ciéncies de l'Espai (CSIC–IEEC), Facultat de Ciéncies, Campus UAB, Torre C5-parell, 2a planta, 08193, Bellaterra (Barcelona), Spain
[2]INAF - OAC, loc. Poggio dei Pini, strada 54, I-09012 Capoterra, Italy.
[3]Dipartimento di Fisica, Università di Padova, via F. Marzolo 8, I-35131 Padova, Italy.
[4]MSSL-UCL, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK.
[5]INAF - OAR, via Frascati 33, I-00040 Monteporzio Catone, Italy.
[6]INAF - IASF Milano, via E. Bassini 15, I-20133 Milano, Italy.
[7]AIM (CEA/DSM-CNRS-Université Paris Diderot), Irfu/Service d'Astrophysique, Saclay, F-91191 Gif-sur-Yvette, France.
[8]Sabancı University, Orhanlı-Tuzla, 34956 İstanbul, Turkey.
[9]NASA Marshall Space Flight Center, Huntsville, AL 35812, USA
*To whom correspondence should be addressed; E-mail: rea@ieec.uab.es.

Soft gamma repeaters and anomalous x-ray pulsars form a rapidly increasing group of x-ray sources exhibiting sporadic emission of short bursts. They are believed to be magnetars, i.e. neutron stars powered by extreme magnetic fields, $B \sim 10^{14} - 10^{15}$ Gauss. We report on a soft gamma repeater with low magnetic field, SGR 0418+5729, recently detected after it emitted bursts similar to those of magnetars. X-ray observations show that its dipolar magnetic field cannot be greater than 7.5×10^{12} Gauss, well in the range of ordinary radio pulsars, implying that a high surface dipolar magnetic field is not necessarily required for magnetar-like activity. The magnetar population may thus

include objects with a wider range of B-field strengths, ages and evolutionary stages than observed so far.

Magnetized, isolated rotating neutron stars are often detected as pulsating sources in the radio and x-ray bands, hence the name pulsars. Pulsars slow down with time as their rotational energy is lost via magnetic dipole radiation. The surface dipolar magnetic field (B) of a pulsar can be estimated using its spin period, P, and spin-down rate, $\dot{P}$, as follows:

$$B = (3\ I\ c^3 \dot{P}\ P/8\pi^2 R^6)^{1/2} \sim 3.2 \times 10^{19} (P\dot{P})^{1/2}\ \mathrm{Gauss} \quad (1)$$

where P is in seconds, $\dot{P}$ in seconds/second, and we assumed $R \sim 10^6$ cm and $I \sim 10^{45}$ g cm^2, which are the neutron star radius and moment of inertia, respectively.

Although this expression was developed to estimate the magnetic fields of radio pulsars, usually $\sim\ 10^{12}$ Gauss, it has been traditionally used also for magnetars, where the derived values of B reach $\sim\ 10^{15}$Gauss (*1*). To date only $\sim\ 16$ of these ultra-magnetized neutron stars have been observed (*5*, 6); their population includes soft gamma repeaters (SGRs) and anomalous x-ray pulsars (AXPs). All known magnetars are x-ray pulsars with luminosities of $L_{\mathrm{X}} \sim 10^{32}$–$10^{36}$ erg s^{-1}, usually much higher than the rate at which the star loses its rotational energy through spin-down. Their high luminosities together with the lack of evidence for accretion from a stellar companion (*7, 8*), led to the conclusion that the energy reservoir fueling the SGR/AXP activity is their extreme magnetic field (*3, 9*). Observationally, magnetars are characterized by stochastic outbursts (lasting from days to years) during which they emit very short x/γ-ray bursts; they have rotational periods in a narrow range (2–12 s) and, compared to other isolated neutron stars, large period derivatives of $\sim 10^{-13} - 10^{-10}$ ß. Their large dipolar $B-$fields and relatively young characteristic ages are estimated to be over $\sim 5 \times 10^{13}$ Gauss, and $t_{\mathrm{c}} = P/2\dot{P}$ ~0.2 kyr - 0.2 Myr [see (*5*) for a review].

In addition to the canonical SGRs and AXPs, two other sources are known to show magnetar-like activity: PSR J1846$-$0258 (*10, 11*) and PSR 1622$-$4950 (*12*). The former is a 0.3 s, allegedly rotation-powered, x-ray pulsar, with a magnetic field of $B \sim 4.8 \times 10^{13}$ Gauss (in the lower end of the magnetar range), from which a typical magnetar outburst and short x-ray bursts were detected. In the latter, flaring radio emission with a rather flat spectrum (similar to those observed in the two transient radio magnetars; (*13, 14*)) was detected from a 4.3 s radio pulsar with a magnetic field in the magnetar range ($B \sim 3 \times 10^{14}$ Gauss).

In all sources with magnetar-like activity, the dipolar field spans $5 \times 10^{13}\,\mathrm{G} < B < 2 \times 10^{15}\,\mathrm{G}$, which is ~ 10–1000 times the average value in radio pulsars and higher than the electron quantum field, $B_{\mathrm{Q}} = m_e^2 c^3/e\hbar \sim 4.4 \times 10^{13}$ Gauss. The existence of radio pulsars with $B > B_{\mathrm{Q}}$ and showing only normal behavior (*15*) is an indication that a magnetic field larger than the quantum electron field alone may not be a sufficient condition for the onset of magnetar-like activity. In contrast, so far the opposite always held: magnetar-like activity was observed only in sources with dipolar magnetic fields stronger than B_{Q}.

SGR 0418+5729 was discovered on 5 June 2009 when the Fermi Gamma-ray Burst Monitor (GBM) observed two magnetar-like bursts (*16*). Follow-up observations with several x-ray satellites show that it has x-ray pulsations at ~9.1 s, well within the range of periods of magnetar sources (*17, 18*). Further studies show that SGR 0418+5729 exhibits all the typical characteristics of a magnetar: i) emission of short x-ray bursts, ii) enhanced persistent flux, iii) slow pulsations with a variable pulse profile, and iv) a x-ray spectrum characterized by a thermal plus non-thermal component, which softened as the outburst decayed.

What made this source distinctly different was the failure of detecting a period derivative in the first 160 days after the outburst onset, despite frequent observational coverage. Several x-ray satellites (*18*) monitored the source almost weekly since its detection. This extensive observational campaign allowed the determination of an accurate ephemeris for the pulsar rotational period, but no sign of a spin down was detected. In the first 160 days after the outburst onset, the upper limit on the period derivative was 10^{-13} ß (90% confidence level), which, according to equation (1), translates into a surface dipolar magnetic field $B < 3 \times 10^{13}$ Gauss (*18*). This limit is quite low for a magnetar source, but not abnormally so, given the detection of a comparable magnetic field in the magnetar-like PSR J1846−0258 (*10*), or the case of AXP 1E 2259+586 with $B \sim 6 \times 10^{13}$ Gauss (*19*).

SGR 0418+5729 could not be monitored for a while after the first 160 days, because the Sun became too close to its position in the sky. On 2010 July 9th, soon after it became observable again, we started an extensive monitoring of the source with the Swift, Chandra and XMM-Newton X-ray satellites (Tab. S1). In particular, on 2010 July 23rd, we detected it with the Advanced CCD Imaging Spectrometer (ACIS) onboard Chandra at a flux of $(1.2 \pm 0.1) \times 10^{-13}$erg s^{-1}cm^{-2} (0.5–10 keV), more than one order of magnitude fainter than in the previous available observation (*18*). The spectrum is well fit by an absorbed blackbody with a line of sight absorption $N_H = (1.5 \pm 1.0) \times 10^{21}$cm^{-2} and $kT = 0.67 \pm 0.11$ keV (all quoted errors are at 90% confidence level). Pulsations were also clearly detected at the known magnetar period. On 2010 September 24th, we observed SGR 0418+5729 with the European Photon Imaging Camera (EPIC) onboard XMM–Newton, which detected it at a comparable flux, and could measure again the rotational period of the neutron star. We used our new Swift, Chandra and XMM–Newton observations, together with several other observations (Tab. S1) and phase-connected all the source data from 2009 June 5th till 2010 September 24th (Fig. 1 and Supporting on-line Material). We found a best fit period of 9.07838827(4) s referred to TJD (Truncated Julian Day) 14993.0 and to the Solar System barycenter. The phase evolution of SGR 0418+5729 is well described by a linear relation $\phi = \phi_0 + 2\pi(t - t_0)/P$, and a quadratic term $-2\pi\dot{P}(t - t_0)^2/2P^2$ (which reflects the presence of a spin down), is not statistically required. This implies an upper limit on the period derivative of SGR 0418+5729 of

$\dot{P} < 6.0 \times 10^{-15}$ß (90% confidence level). This value is the smallest of all known SGRs/AXPs, of the two magnetar-like pulsars PSR J1846−0258 and PSR 1622−4950, and of the X-ray Dim Isolated Neutron Stars (XDINSs; *20*) for which a measure of $\dot{P}$ is available (Fig. 2). The corresponding limit on the surface dipolar magnetic field of SGR 0418+5729 is $B < 7.5 \times 10^{12}$ Gauss, making it the magnetar with the lowest surface dipolar magnetic field yet. The upper limit on the period derivative implies a characteristic age of the source $t_{\rm c} > 24$ Myr.

Despite the characteristic age is known to overestimate the true age of a neutron star in which magnetic field decay occurred (*25*), as is likely the case of SGR 0418+5729, the rather high Galactic latitude ($b = 5.1$ deg) and its position on the P–$\dot{P}$ plane [close to the death line for radio emission (*26,27*)], suggest that this system is quite older than the other SGRs/AXPs.

The existence of magnetar-like sources with low values of B has several consequences. Among isolated pulsars, which are presumably rotation-powered, $\sim$18% have a dipolar magnetic field higher than the upper limit we derived for SGR 0418+5729 (Fig. 2). The discovery of PSR 1622−4950 (*12*) on the other hand, suggests that magnetar-like behavior may manifest itself mostly in the radio band. In this framework, our result indicates that a large number of apparently normal pulsars might turn on as magnetars at anytime, regardless of having a surface dipole magnetic field above the quantum limit or not. As a direct consequence, magnetar-like activity may occur in pulsars with a very wide range of magnetic fields and it may fill a continuum in the $P - \dot{P}$ diagram (Fig. 2).

So far we have been considering the relationship between the surface dipolar magnetic field and magnetar-like activity. However, it is likely that the magnetar activity is driven by the magnetic energy stored in the internal toroidal field (*3, 4*); this component cannot be measured directly. If the magnetar model as it is currently understood is indeed valid, despite its low surface dipolar field, SGR 0418+5729 is expected to harbor a sufficiently intense internal toroidal component $B_{\rm tor}$ in order to be able to undergo outbursts and emit bursts. This large internal field can stress the crust and ultimately deforms/cracks the star surface layers, periodically allowing magnetic helicity to be transferred to the external field, thus causing the (repeated) short x-ray bursts and the overall magnetar-like activity (*3,21, 22*).

As with other magnetars, $B_{\rm tor}$ can be estimated assuming that the magnetic energy stored in the internal toroidal field powers the quiescent emission of SGR 0418+5729 during its entire lifetime, $B^2_{\rm tor} \sim 6L_{\rm X}t_{\rm c}/R^3_{\rm NS}$ (*3*). Assuming a source distance of 2 kpc (*16, 18*), and that the current luminosity $L_{\rm X} \sim 6.2 \times 10^{31}$erg s^{-1} (the lowest measured so far for this source) corresponds to the quiescent luminosity, we obtain $B_{\rm tor} \sim 5 \times 10^{14}$ Gauss for a neutron star radius of $R_{\rm NS} = 10^6$ cm and a source characteristic age of $t_{\rm c} \sim 24$ Myr. A value of the same order is obtained if the ratio of the toroidal to poloidal field strength is ~ 50, as in the magneto-thermal evolution scenario (*23*, 24). In this picture, SGR 0418+5729 may possess a high enough internal magnetic field to overcome the crustal yield and give rise to magnetar-like activity despite its low surface dipolar magnetic field. However, would the actual measurement of the surface dipolar B-field of SGR 0418+5729 turn out to be much smaller than the present upper limit, this may require to rethink some of the ingredients at the basis of the magnetar scenario.

SGR 0418+5729 may represent the tip of the iceberg of a large population of old and low-dipolar-field magnetars that are dissipating the last bits of their internal magnetic energy (*29*). Indeed, a large fraction of the radio pulsar population may have magnetar-like internal fields not reflected in their normal dipolar component.

References and Notes

1. We note that the surface dipolar magnetic field of magnetars has been estimated also with several other methods (*2,3,4*); these give values consistent with those derived from the formula in eq.(1) .

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24. Note that the internal field strength required to produce crustal cracking should be typically in excess of 10^{14} Gauss (*3*).

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29. Note that if among these were young, fast spinning young pulsars, the resulting magnetically-induced ellipticity would lead to powerful emission of periodic gravitational waves.

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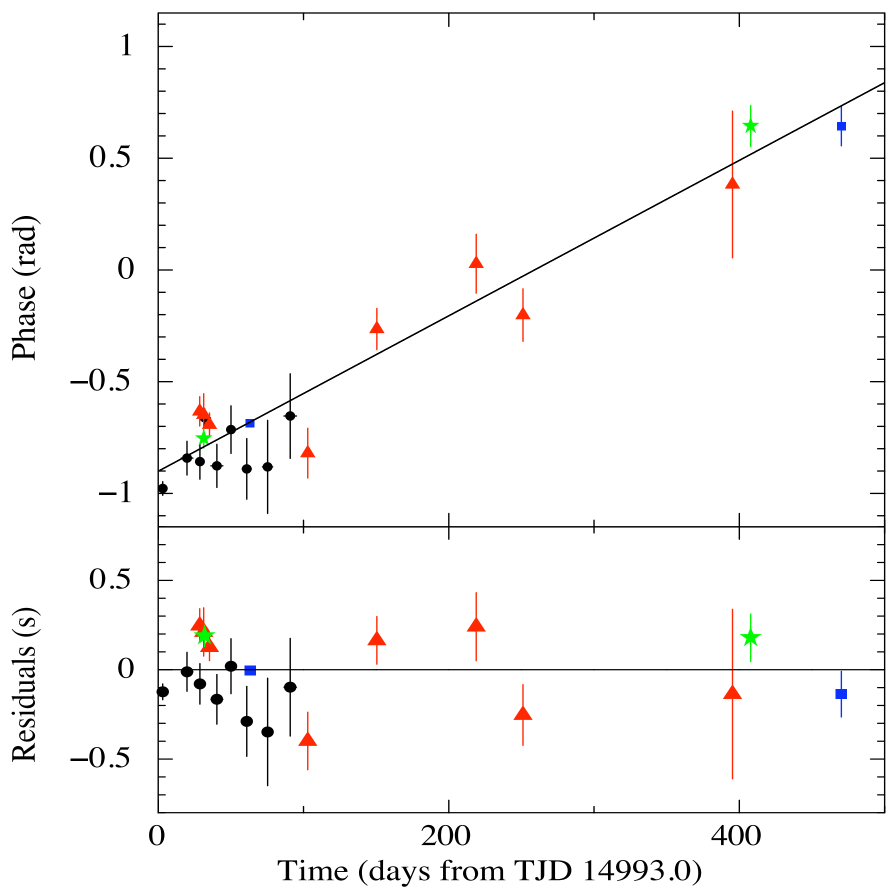
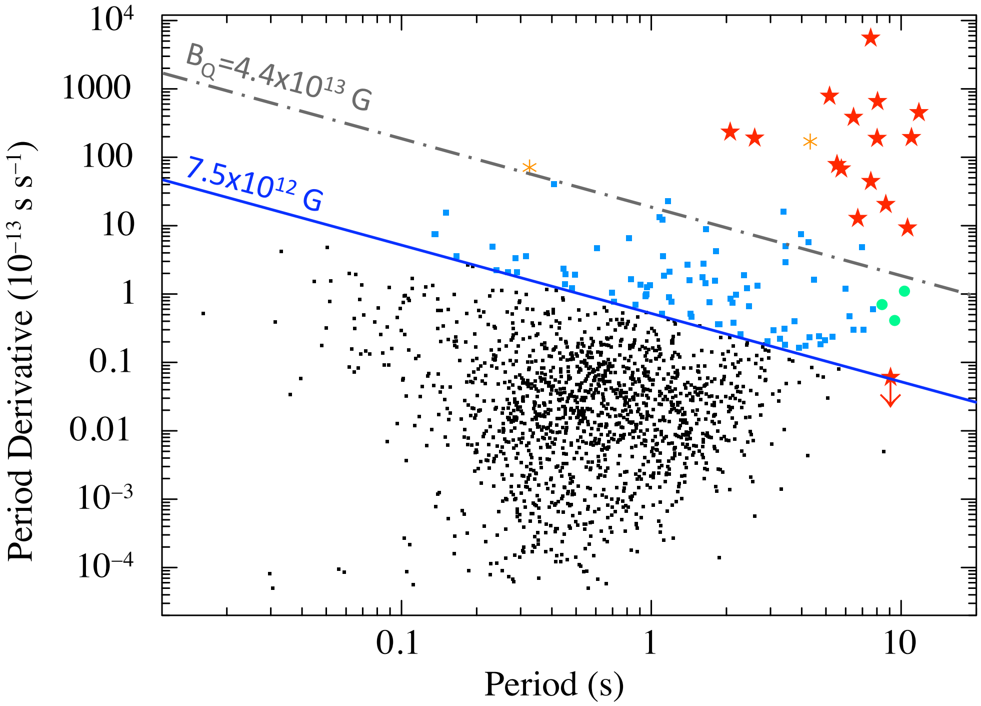


Phase (rad)
Residuals (s)
Time (days from TJD 14993.0)
1
0.5
0
−0.5
−1
0.5
0
−0.5
0
200
400

Fig. 1. Top panel: rotation phase versus time for the coherent timing solution for SGR 0418+5729 obtained using data taken with Rossi X-ray Timing Explorer (black circles), Swift (red triangles) XMM–Newton (blue squares), and Chandra (green stars). The solid line shows the best-fitting linear function ($\chi^2 = 1.8$ for 18 degrees of freedom; root mean square $\sim 3\%$). Bottom panel: fit residuals.



B_Q=4.4x10^13 G
7.5x10^12 G
Period Derivative (10^{-13} s s^{-1})
Period (s)
10^4
1000
100
10
1
0.1
0.01
10^{-3}
10^{-4}
0.1
1
10

Fig. 2. P–$\dot{P}$ diagram for all known isolated pulsars [data are from (*28*)]. $\dot{P}$ is in units of 10^{-13} ß. Black squares represent normal radio pulsars, light-blue squares normal radio pulsars with a magnetic field larger than 7.5×10^{12} Gauss (our limit for SGR 0418+5729), red stars are the magnetars, orange asterisks are the magnetar-like pulsars PSR J1846$-$0258 and PSR 1622$-$4950, and the green circles are the X-ray Dim Isolated Neutron Stars (XDINSs). The blue solid line marks the 90% upper limit for the dipolar magnetic field of SGR 0418+5729. The value of the electron quantum magnetic field is also reported (dash-dotted grey line).