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Figs. S1 and S2

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A Low-Magnetic-Field Soft Gamma Repeater

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Soft gamma repeaters (SGRs) 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, that is, neutron stars powered by extreme magnetic fields, $B \sim 10^{14}$ to 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:

$$B = (3Ic^3 P\dot{P}/8\pi^2 R^6)^{1/2} \sim 3.2 \times 10^{19} (P\dot{P})^{1/2}\,\mathrm{G} \tag{1}$$

where P is in seconds and $\dot{P}$ is in seconds/seconds; 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 (G), it has been traditionally used also for magnetars, where the derived values of B reach $\sim 10^{15}$ G (1). To date, only ~16 of these ultramagnetized neutron stars have been observed (2, 3); their population includes soft gamma repeaters (SGRs) and anomalous x-ray pulsars (AXPs). All known magnetars are x-ray pulsars with luminosities of $L_X \sim 10^{32}$ to 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 (4, 5) led to the conclusion that the energy reservoir fueling the SGR/AXP activity is their extreme magnetic field (6, 7). Observationally, magnetars are characterized by stochastic outbursts (lasting from days to years) during which they emit very short x-ray and γ-ray bursts; they have rotational periods in a narrow range (2 to 12 s) and, compared with other isolated neutron stars, large period derivatives of $\sim 10^{-13}$ to 10^{-10} s s^{-1}. Their large dipolar B fields and relatively young characteristic ages (t_c) are estimated to be more than $\sim 5 \times 10^{13}$ G, and $t_c = P/2\dot{P} \sim 0.2$ thousand years to 0.2 million years [see (2) for a review].

In addition to the canonical SGRs and AXPs, two other sources are known to show magnetar-like activity: PSR J1846−0258 (8, 9) and PSR 1622−4950 (10). The former is a 0.3 s, allegedly rotation-powered, x-ray pulsar, with a magnetic field of $B \sim 4.8 \times 10^{13}$ G (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 (11, 12)] was detected from a 4.3-s radio pulsar with a magnetic field in the magnetar range ($B \sim 3 \times 10^{14}$ G).

In all sources with magnetar-like activity, the dipolar field spans $5 \times 10^{13}\ \mathrm{G} < B < 2 \times 10^{15}$ G, which is ~10 to 1000 times the average value in radio pulsars and higher than the electron quantum field, $B_Q = m_e^2 c^3/e\hbar \sim 4.4 \times 10^{13}$ G. The existence of radio pulsars with $B > B_Q$ and showing only normal behavior (13) 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 (14).

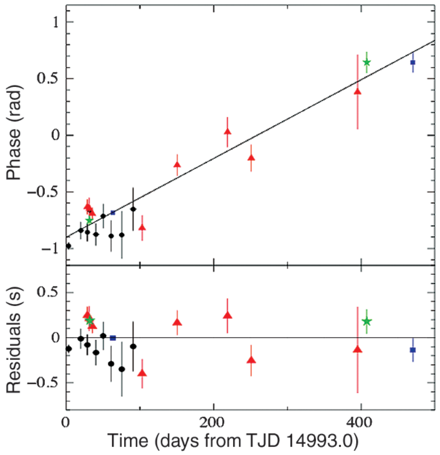

Fig. 1. (**Top**) Rotation phase versus time for the coherent timing solution for SGR 0418+5729 obtained using data taken with Rossi X-ray Timing Explorer (black circles), Swift (red triangles), XMM-Newton (blue squares), and Chandra (green stars). The solid line shows the best-fitting linear function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

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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 (*15*, *16*). 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) an x-ray spectrum characterized by a thermal plus nonthermal 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 (*16*) 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} s s^{-1} (90% confidence level), which, according to Eq. 1, translates into a surface dipolar magnetic field $B < 3 \times 10^{13}$ G (*16*). 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 (*8*), or the case of AXP 1E 2259+586 with $B \sim 6 \times 10^{13}$ G (*17*).

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 9 July 2010, soon after it became observable again, we started an extensive monitoring of the source with the Swift, Chandra, and X-ray Multi-mirror Misson–Newton (XMM-Newton) x-ray satellites (table S1). In particular, on 23 July 2010, we detected it with the Advanced Charge-Coupled Device Imaging Spectrometer (ACIS) onboard Chandra at a flux of $(1.2 \pm 0.1) \times 10^{-13}$ erg s^{-1} cm^{-2} (0.5 to 10 keV), more than one order of magnitude fainter than in the previous available observation (*16*). 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 24 September 2010, 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 (table S1) and phase-connected all the source data from 5 June 2009 until 24 September 2010 (Fig. 1 and Supporting Online 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 $\varphi = \varphi_0 + 2\pi(t - t_0)/P$, 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 $\dot{P} < 6.0 \times 10^{-15}$s s^{-1} (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) (*18*) 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 $B < 7.5 \times 10^{12}$ G, 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 $t_c > 24$ million years.

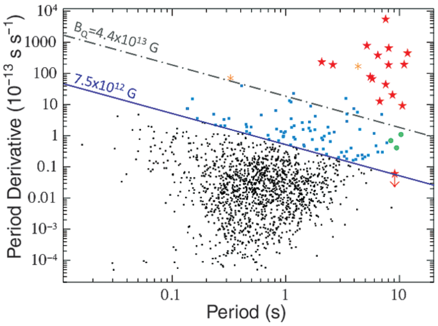

Fig. 2. P–$\dot{P}$ diagram for all known isolated pulsars [data are from (*29*, *30*)]. $\dot{P}$ is in units of 10^{-13} s s^{-1}. Black squares represent normal radio pulsars, light-blue squares are normal radio pulsars with a magnetic field larger than 7.5×10^{12} G (our limit for SGR 0418+5729), red stars are the magnetars, orange asterisks are the magnetar-like pulsars PSR J1846–0258 and PSR 1622–4950, and green circles are the 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 gray line).

Although the characteristic age is known to overestimate the true age of a neutron star in which magnetic field decay occurred (*19*), 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 pulsars, below which the radio emission is supposed to be halted (*20*, *21*)], suggest that this system is quite a lot 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, ~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 (*10*), 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 any time, regardless of whether the surface dipole magnetic field is above the quantum limit. 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 (*6*, *22*); 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_{tor} in order to be able to undergo outbursts and emit bursts. This large internal field can stress the crust and ultimately deforms and 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 (*6*, *23*, *24*).

As with other magnetars, B_{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, $B_{tor}^2 \sim 6L_X t_c/R_{NS}^3$ (*6*). Assuming a source distance of 2 kpc (*14*, *16*), and that the current luminosity $L_X \sim 6.2 \times 10^{31}$ erg s^{-1} (the lowest measured so far for this source) corresponds to the quiescent luminosity, we obtain $B_{tor} \sim 5 \times 10^{14}$ G for a neutron star radius of $R_{NS} = 10^6$ cm and a source characteristic age of $t_c \sim 24$ million years. 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 (*25*, *26*). 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, should the actual measurement of the surface dipolar B field of SGR 0418+5729 turn out to be much smaller than the present upper limit, it may be necessary 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 (*27*). Indeed, a large fraction of the radio pulsar population may have magnetar-like internal fields not reflected in their normal dipolar component.

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Table S1
References

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Anomalous Strength Characteristics of Tilt Grain Boundaries in Graphene

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Graphene in its pristine form is one of the strongest materials tested, but defects influence its strength. Using atomistic calculations, we find that, counter to standard reasoning, graphene sheets with large-angle tilt boundaries that have a high density of defects are as strong as the pristine material and, unexpectedly, are much stronger than those with low-angle boundaries having fewer defects. We show that this trend is not explained by continuum fracture models but can be understood by considering the critical bonds in the strained seven-membered carbon rings that lead to failure; the large-angle boundaries are stronger because they are able to better accommodate these strained rings. Our results provide guidelines for designing growth methods to obtain sheets with strengths close to that of pristine graphene.

Graphene is one of the thinnest materials ever synthesized, yet it is one of the strongest ever measured (*1*, *2*), and it exhibits exceptional electronic, thermal, and optical properties (*1*, *3*); however, growing large-area, single-layer graphene sheets remains a major challenge. Recently, a chemical vapor deposition (CVD) technique has been devised that exploits the low solubility of carbon in metals such as nickel (*4*, *5*) and copper (*6*, *7*) in order to grow graphene on metal foils. A consequence of this technique is that the large-area graphene sheets contain grain boundaries, because each grain in the metallic foil serves as a nucleation site for individual grains of graphene (*6*).

Tilt grain boundaries in graphite had first been observed in scanning tunneling microscopy (STM) experiments by Albrecht *et al.* (*8*), and since then several groups have performed similar microscopy studies (*9*–*14*). More recently, Hashimoto *et al.* (*15*) have observed individual dislocations in graphene using transmission electron microscopy (TEM), and the structure, as well as the electronic, magnetic, and dynamical properties of grain boundaries in graphene have been investigated by a number of other research teams (*16*–*18*). With all this previous work established, a natural question to ask is how these grain boundaries influence the mechanical properties of graphene. Given the fact that graphene is one of the stiffest (modulus ~ 1 TPa) and strongest (strength ~ 100 GPa) materials, in order to use CVD-synthesized graphene sheets in nano-electromechanical systems (NEMS), in sensors, and as pressure barriers, it is important to know how the grain boundaries influence these fundamental mechanical properties.

Although a number of studies have been carried out on the mechanics of dislocations and defects in carbon nanotubes (*19*–*21*) and graphene (*22*), the mechanical properties of hydrogen-functionalized graphene (*23*), and the fracture and failure of graphene and carbon nanotubes with multiple vacancies (*24*) and Stone-Wales defects (*24*–*26*), the effect of grain boundaries on the mechanical properties of graphene has been largely neglected. To address this outstanding problem, we have

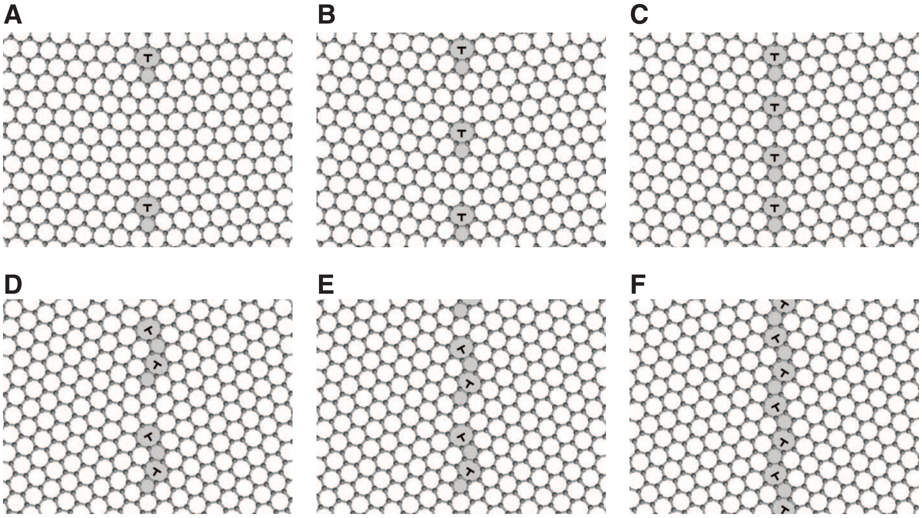

Fig. 1. The structures of grain boundaries in (**A** to **C**) zigzag-oriented and (**D** to **F**) armchair-oriented graphene sheets with varying mismatch angles.

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ERRATUM

Post date 17 December 2010

Reports: "A low-magnetic-field soft gamma repeater" by N. Rea *et al.* (12 November, p. 944). Paolo Esposito's affiliation contained an error. He is at the Osservatorio Astronomico di Cagliari. The affiliation has been corrected in the HTML version online.