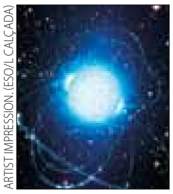
# Magnetars: a problem and a solution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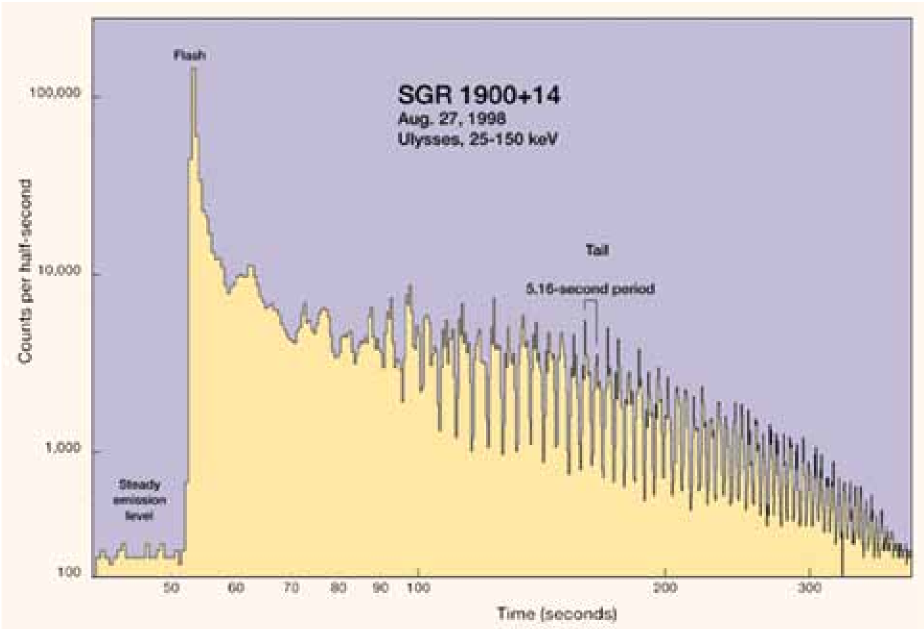
In this issue's cover feature, **Simon Clark** explores routes to understanding the formation of magnetars, neutron stars with extreme magnetic fields.




**2** X-ray lightcurve of the 1998 giant flare exhibited by SGR 1900+14, illustrating the initial, rapid high-energy "spike" and the subsequent softer pulsationally modulated tail characteristic of all these events. (NASA/Marshall Space Flight Center; Feroci *et al.* 2001)

By 1979 the first detection of a gamma-ray burst (GRB) was over a decade in the past and a recognition of their true nature – the death of massive stars or the coalescence of two relativistic stellar corpses – lay over a decade in the future. One such event, GB790107, attracted little attention in January of that year, save for the recognition that its spectrum peaked at much lower – softer – energies than expected for canonical GRBs. In retrospect, this was an important clue to the fact that GB790107 fundamentally differed from other GRBs. The detection of the second member of this new class of astrophysical object was not met with such indifference. On 5 March 1979, a flash of gamma rays swept through the solar system with such intensity that satellite-mounted radiation detectors were sequentially saturated as the wavefront overtook them.

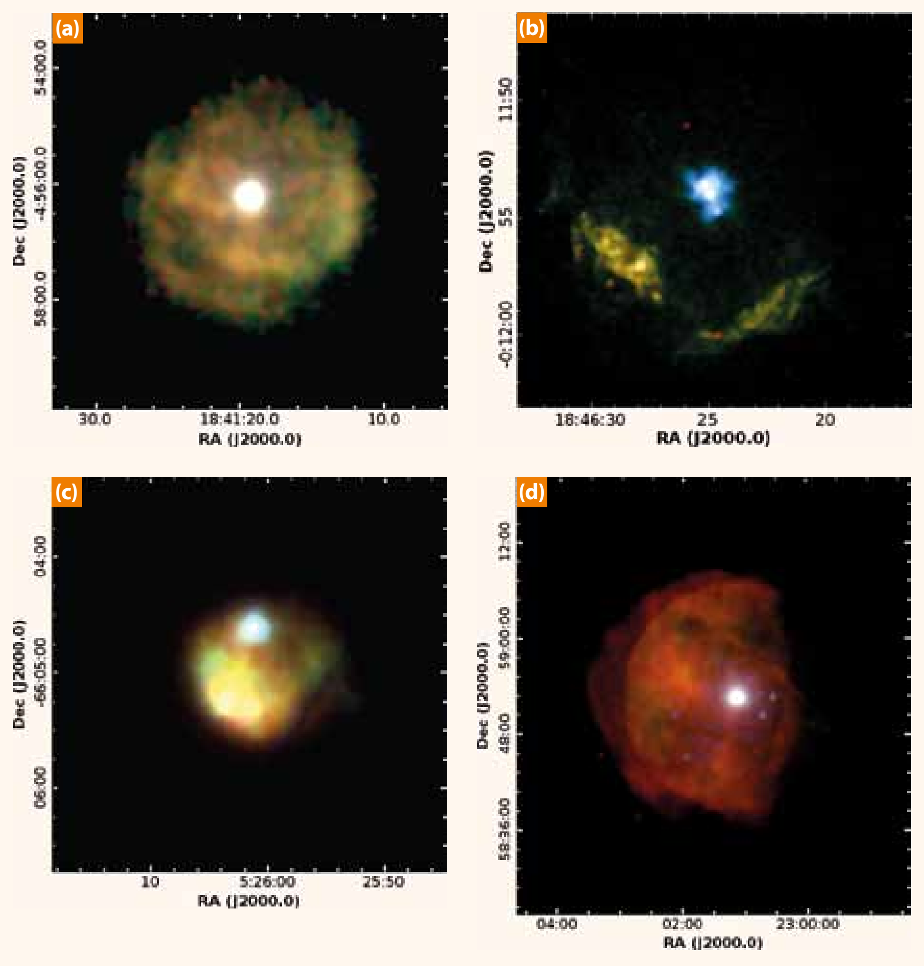
At this time a key barrier to the interpretation of GRBs was a lack of accurate positional information and hence distance and luminosity estimates; most contemporaneous theories posited an origin within our galaxy. The multiple detections of this bright GRB provided a unique opportunity, with analysis of the differing arrival times of the photons at individual satellites permitting the determination of a precise location of the flare. It came from a supernova remnant in the Large Magellanic Cloud (LMC; Evans *et al.* 1980) – a huge surprise. Moreover, the resultant distance determination made possible an evaluation of the energy budget and the result was staggering: in 0.2 s, the flare carried away as much energy as the Sun releases in a thousand years (Mazets *et al.* 1979a, Evans *et al.* 1980).

Unlike other GRBs known at the time, which were singular events, multiple bursts followed from the same place in the sky over the next four years, albeit of significantly lower flux and with a softer spectrum than the high-luminosity ~0.2 s gamma-ray pulse that heralded the giant flare of 5 March. Continued monitoring revealed that GB790107 shared this repetitive nature (e.g. Laros *et al.* 1987) and a third member of this grouping was quickly identified (Mazets *et al.* 1979b). Given their unknown physical nature – both their rapidity and peak luminosities distinguished them from accretion-powered sources – from their observational properties they were dubbed soft gamma repeaters (SGRs).

**"These objects offer the potential to study processes that cannot be replicated on Earth"**

Nearly two decades elapsed before a second giant flare was observed, this time from SGR 1900+14 (figure 2). Crucially, as with the 5 March event SGR 0526-66, the detection of periodic flux modulations in the latter phases of both eruptions ($P \sim 8$ s and ~5.16 s respectively; Mazets *et al.* 1979a, Hurley *et al.* 1999) provided compelling evidence for their association with slowly rotating neutron stars. The detection of comparable pulsations in the quiescent flux of SGR 1806-20 ($P \sim 7.47$ s; Kouveliotou *et al.* 1998) affirmed this identification. Subsequently, on 27 December 2004, SGR 1806-20 eclipsed both siblings by unleashing the most energetic explosion witnessed within the galaxy for over 400 years. Assuming isotropic emission, $\sim 1.2 \times 10^{46}$ erg were released in the initial 0.2 s gamma-ray spike, an event instantaneously ~300 times brighter than all the stars in the galaxy put together (Hurley *et al.* 2005, Bibby *et al.* 2008). Unlike the progenitors of supernovae, SGR 1806-20 was not destroyed by this conflagration. What, then, was the origin of the emission in SGRs?

Contemporaneously, a parallel problem was identified for the class of neutron stars denoted anomalous X-ray pulsars (AXPs). Unlike normal radio pulsars, these were persistently bright X-ray sources, leading to the obvious hypothesis that they were X-ray binaries, powered by accretion of material from a companion star. However, deep optical imaging failed to identify the expected stellar counterparts – just as they had not been found for the SGRs. Intriguingly, the AXPs and SGRs also shared comparable pulsational periods, suggesting a kinship. With the detection of rapid SGR-like X-ray bursts from the AXP 1E 1048.1-5937 (Gavriil




**3** X-ray images of supernova remnants containing magnetars (the bright point sources) with energies colour coded (red: 0.3–1.0 keV, green: 1.0–3.0 keV and blue: 3.0–10.0 keV). (a): Kes 73 hosts magnetar 1E 1841-045. (b): Kes 75 hosts PSR J1846-0258. (c): N49 hosts SGR 0526-66. (d): CTB109 hosts 1E 2259+586. (Reproduced, by kind permission, from Martin *et al.* 2014)

*et al.* 2002) it was clear that both flavours of neutron star were one and the same, with their differing nomenclatures a relic of their discovery modes, during flares (SGRs) or via quiescent emission (AXPs).

## A physical explanation

If the emission from SGRs and AXPs was not the result of gravitational potential released via accretion from a companion, then what was its energy source? Young, rapidly spinning radio pulsars are powered by the gradual extraction of their rotational energy, leading them to spin down over time. The agent for this is the magnetic field anchored to the surface which, as it rotates with the neutron star, generates dipole radiation and winds of charged particles that carry the energy away. However, the relatively long rotational periods of SGRs and AXPs mean that this energy source is insufficient to power their emission.

Young neutron stars are very hot, with surface temperatures of $\sim10^5$–$10^6$ K, so a reasonable assumption might be that the radiation in SGRs and AXPs results from residual heat. However, this does not explain the origin of the rapid bursting that characterizes SGRs, nor the ubiquitous initial gamma-ray spike that characterized the giant flares of SGR 0526-66, 1900+14 and 1806-20.

A solution to this enigma was outlined in a series of landmark papers by Robert Duncan and Chris Thompson (e.g. Duncan & Thompson 1992, Thompson & Duncan 1993, 1995, 1996). In these works they suggested the existence of magnetars – hypothetical neutron stars possessing an extremely strong magnetic field – before describing a possible route to their formation and associating them first with SGRs and then AXPs. Specifically, they proposed that magnetars supported **B**-fields of $\sim10^{14}$–$10^{15}$ G, with both exterior and interior components – the former likely to be dipole and observationally accessible, the latter toroidal and hidden from direct view. For context, a typical fridge magnet has a **B**-field of ~100 G, those found in sunspots are ~4000 G, and the strongest fields typically exhibited by radio pulsars are $\sim10^{12}$–$10^{13}$ G. The field suggested for magnetars exceeds that which we can routinely generate by electromagnets by eight orders of magnitude; in addition, it is greater than the quantum electrodynamic field strength ($B_{QED} \sim m_e^2c^3/\hbar e \sim 4.4\times10^{13}$ G; the point at which the energy between Landau levels of electrons equals their rest mass). These objects offer the potential to study a range of physical processes that cannot be replicated on the Earth (c.f. Duncan 2000).

The magnetar hypothesis provided a framework under which the bright quiescent X-ray emission and the energetic bursts and flares of SGRs and AXPs could be understood, because the decay of the magnetic field, in principle, provides a sufficiently large reservoir of energy to explain both. For example, a $10^{15}$ G field will support a quiescent luminosity of $\sim10^{35}$ erg s$^{-1}$ for $10^5$ years, compatible with the plausible lifetime for a magnetar ($\sim10^4$–$10^5$ yr; e.g. Mereghetti 2013). However, with $\sim10^{44}$–$10^{46}$ erg being released in the three giant outbursts observed to date, such an energy reservoir ($\sim3\times10^{47}$ erg) does place limits on the frequency of their occurrence.

Moreover, the surprisingly long rotational periods of magnetars in comparison to other radio pulsars are also explicable in this model, because an extreme **B**-field will permit rapid and efficient spin-down via dipole radiation and a possible contribution from a pulsar wind (Duncan 2000). Duncan & Thompson (1992) used this mechanism and the apparent youth of SGR 0526-66 – suggested by its possible association with the supernova remnant N49 (figure 3) – to estimate a **B**-field of $\sim6\times10^{14}$ G for an adoptive age of $\sim10^4$ yr. No measurement of the spin-down rate of SGR 0526-66 was possible at the time. But six years later, Kouveliotou *et al.* (1998, 1999) directly measured the dramatic spin-down of first SGR 1806-20 and then SGR 1900+14, from which they inferred a magnetic field between about 2 and $8\times10^{14}$ G for both objects, spectacularly confirming theoretical predictions.

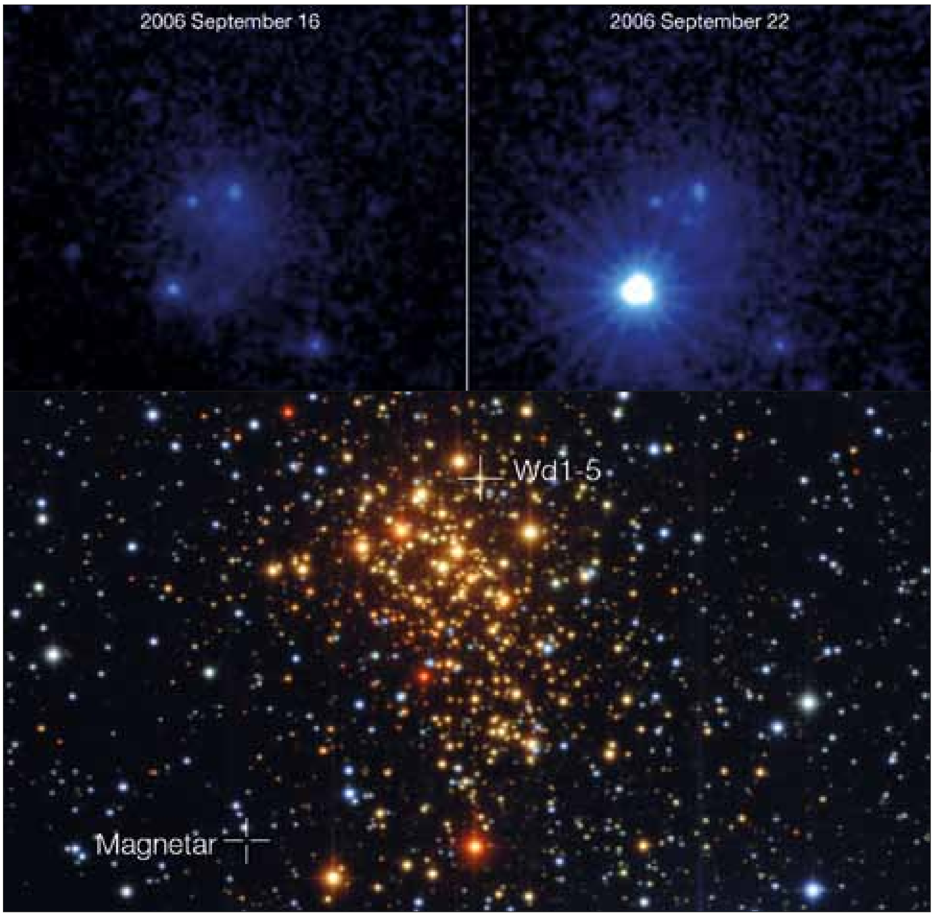
## Emission mechanisms

An immediate question is: how does the energy released by the evolution and decay of the interior and exterior components of the **B**-field lead to the diverse X-ray behaviour of magnetars (e.g. Mereghetti 2013)? Current models suggest that neutron stars possess a crust of atomic nuclei forced into a solid lattice with electrons flowing between them. Moving inwards, the nuclei become increasingly massive and neutron-rich, suffused by a sea of electrons and neutrons. Below the crust is a superdense liquid core with densities of $>10^{14}$ g cm$^{-3}$ and an uncertain composition, although a neutron superfluid and a proton superconductor are expected to be present (potentially with more exotic states of matter). The interior, toroidal component of the magnetic field permeates the core, pulling on the crust above, to which the external poloidal field is anchored. Over time the stress builds up in the crust, deforming it and consequently distorting the external field. Eventually, the stresses become so great that the crust fractures and/or the external field is rearranged, violently releasing the stored energy in a "star quake".

This release of energy is thought to generate X-ray emission, through two possible mechanisms. If the energy is deposited deep within the crust, as a result of a fracture or plastic deformation, it will diffuse outwards leading to surface heating known as a thermal echo, and thus X-ray emission. Rearrangement of the external magnetic field can generate X-rays by the production of energetic charged particles (electrons, protons and ions) which subsequently impact – and consequently heat – the surface; the electrons may also scatter extant X-ray photons to high energies. These processes are expected to produce rapid (~0.01–1 s), bright (~$10^{38}$–$10^{42}$ erg s$^{-1}$), hard X-ray bursts, as well as long-duration outbursts, in which the persistent flux increases by ~10–100 times quiescent levels before decaying back over timescales between months and years. An example of this sort of flare is shown in the upper panels of figure 4, where it is most probably a result of the rapid heating and subsequent slow cooling of the stellar surface. With only three examples observed to date, the physical mechanism yielding the giant flares is uncertain, but current suggestions mirror those above: i.e. a build up of elastic energy in the crust causing a major fracture or the gradual injection of energy into the external magnetosphere, which subsequently undergoes a large-scale rearrangement due to an unspecified instability.

It is worth noting that the properties of bursts and giant flares provide corroborative evidence for the presence of extreme **B**-fields in magnetars. First, they render plasma largely transparent to X-ray radiation (by suppressing the electron opacity; Paczynski 1992), permitting extreme luminosities. Second, it takes **B**-fields of >$10^{14}$ G to restrain the electron–positron fireball produced during giant flares to a localized region of the surface of the magnetar; it is the rotation of this "captured fireball" into and out of our line-of-sight that has led to the pulsationally modulated X-ray emission visible at late times during an outburst.

The reservoir of magnetic energy must be finite, suggesting that active magnetars last about $10^4$–$10^6$ years before both internal and external components of the magnetic field have decayed below levels where outbursts and flares are possible. Theoretical analysis suggests that magnetar flaring is still possible even if the surface field has decayed, if a strong internal field remains. With $B \leq 7.5 \times 10^{12}$ G, the recently discovered SGR 0418+5729 may represent such a star (Rea *et al.* 2010). Predictions for such systems suggest that they would possess a lower quiescent flux and a reduced frequency of outbursts, so a large number of such systems may await detection.




**4** Top: XMM-Newton observations of magnetar CXOU J164710.2-455216, made 4.3 days before and 1.5 days after a 20 ms long X-ray burst that radiated ~$10^{37}$ erg, the quiescent or persistent X-ray emission being >2 orders of magnitude greater post-burst (Muno *et al.* 2007). Bottom: Optical image of host cluster Westerlund 1, showing both the magnetar and Wd 1-5, a blue hypergiant star with physical properties consistent with it evolving in tandem with the magnetar progenitor in a putative close binary.

## Formation schemes

While the magnetar hypothesis successfully explains a wealth of observational data, the interlinked questions of how the extreme magnetic fields are generated and which stars form magnetars remain unsolved. Two physical processes have been advanced to explain. The first, following Duncan & Thompson (1992), supposes that the **B**-field arises from dynamo action in a manner analogous to that in the Earth and the Sun. If the stellar core is rotating very rapidly at collapse, then any seed field will be rapidly amplified by the rotational and convectional motion of the nuclear fluid comprising the core of the proto-neutron star. This process occurs over very short timescales (~10–20 s) and results in a neutron star with a very short rotational period (of the order of 1 ms) and $B > 10^{14}$ G, which subsequently spins down via dipole radiation and wind losses to the observed range for magnetars (~2–12 s).

The major objection to this scenario is that it requires the progenitor star to be rapidly rotating at the time of supernova; stellar evolution theory suggests that this is problematic. Specifically, angular momentum will constantly be carried away from such stars throughout their lifecycle by their powerful stellar winds. Moreover, if a magnetic field is present, it will physically couple the stellar core to the mantle above. Because it is expected that massive stars pass through a blue and/or a red supergiant phase prior to supernova, this mechanism will very efficiently transfer angular momentum from the rapidly rotating core to the greatly distended and slowly rotating outer layers of the supergiant; thus the former spins down beyond the point at which dynamo action will yield a magnetar.

The second possibility is that magnetars arise from highly magnetic progenitors: the "fossil field" hypothesis. Following from Maxwell's equations, the collapse of the progenitor's core by a length factor of ~$10^5$ in turn leads to an increase in the strength of an existing **B**-field by a factor of ~$10^{10}$, with no need for rapid core rotation. But it would require a progenitor with a core field of about $10^4$–$10^5$ G to form a magnetar in this way. This inevitably begs the question of whether such fossil **B**-fields can form in the first place. Two mechanisms have been proposed: that they are remnants of

**5** Composite false-colour image of the pulsar SXP 1062 and associated supernova remnant (centre right) and nearby massive star-forming region NGC 602 (centre left) at optical (red and and green: AURA/NOAO/CTIO/Univ. Potsdam/L Oskinova *et al.* 2013) and X-ray (blue: NASA/CXC/Univ. Potsdam/L Oskinova *et al.* 2013 & ESA/XMM-Newton) wavelengths.

fields that threaded the molecular cloud from which the star formed, or that they result from strong binary interaction and/or merger, where they may be formed via dynamo action (e.g. Langer 2013). However, such **B**-fields would have to persist throughout post-main-sequence evolution, when the deep convective cores and envelopes of red supergiants appear inimical to their long-term survival. The flip side of this process is that if a **B**-field persists, then core–envelope coupling would lead to a slowly rotating neutron star; not an issue for the formation of magnetars under this scenario, but potentially problematic for producing rapidly rotating pulsars with high-**B**-fields (Spruit 2008).

Finally, we note that these mechanisms form magnetars from massive stars at the point of core-collapse. Alternatively, a rapidly rotating magnetar may form via the merger of two degenerate objects (e.g. white dwarfs or low-mass neutron stars; Metzger *et al.* 2008) as suggested by the properties of a subset of short GRBs. But the latter mechanism would depend on the existence of a hard equation of state for nuclear matter in order to permit the (transitory?) existence of the resultant high-mass neutron star.

## Statistical tests

Can either formation scheme be subject to observational testing? In principle, if one knows the sizes of both the progenitor (dynamo or fossil-field) and magnetar populations one can then determine if the former is sufficient to yield the latter. Unfortunately, assessment of the dynamo scenario requires a determination of the rotation rate of the stellar core. This may be inferred from the surface rotational velocity, but such measurements are complicated by the dense winds of stars at the point of supernova. Similarly, difficulties regarding the inference of the internal **B**-field from the external component complicate evaluation of the fossil-field pathway. Moreover, OB stars displaying detectable surface B-fields appear comparatively rare: the BOB survey made only five detections from a sample size of 98 OB stars (Morel *et al.* 2014) while, independently, the MiMeS study reported 38 detections from 525 stars (Wade *et al.* 2014). Bearing in mind that it is not obvious that the subset of magnetic stars will possess core fields of sufficient strength (>$10^4$ G) to yield a magnetar, nor whether they might persist through a supergiant phase, one might plausibly suggest a resultant fraction of <10% of the total OB star population.

On the flip side, the poorly constrained lifetimes and outburst/flaring cycles of magnetars present a significant barrier to constructing an accurate census. For instance, Muno *et al.* (2008) demonstrated that as a result of these uncertainties, the number of faint, transient magnetars in our galaxy – the most difficult to detect – could range from 80 to 580. Observations by the Swift and Fermi satellites appear to corroborate this hypothesis: in the 25 years before the launch of Swift in 2005, only 10 magnetars were discovered, while 11 identifications have followed over the subsequent nine-year period (Olausen & Kaspri 2014, who also list five more candidate systems).

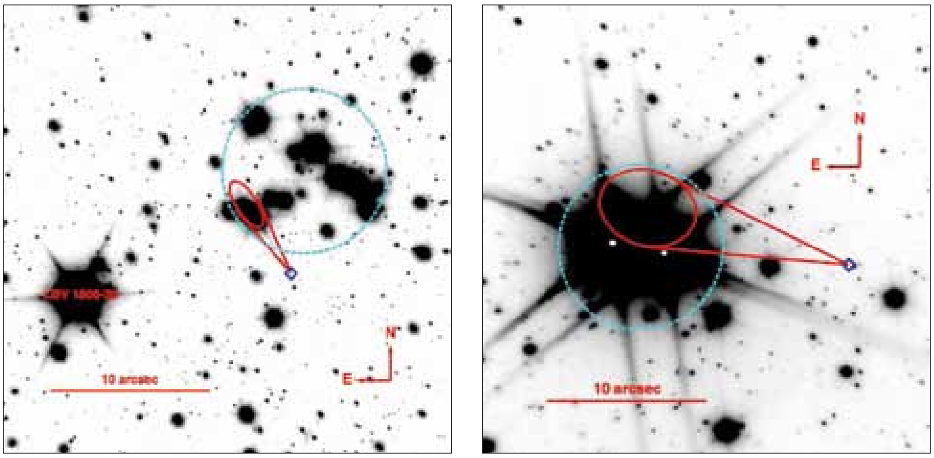
Moreover, in 2006 the young radio pulsar PSR J1846-0258 exhibited the characteristically rapid X-ray bursts of SGRs (Gavriil *et al.* 2008), suggesting an extension of the magnetar phenomenon to neutron stars which had hitherto been thought to be exclusively powered by rotational energy. Likewise, it has recently been suggested that a subset of accretion-powered X-ray binaries may also harbour neutron stars with magnetar-strength **B**-fields (Reig *et al.* 2012). Specifically, the neutron stars within these systems are found to have very long rotational periods (>$10^3$ s) which are most naturally explained by the propellor mechanism, in which an extreme **B**-field couples an initially rapidly rotating neutron star to slowly rotating accreting gas. The result is efficient transport of angular momentum from the former to the latter, leading to prompt spin-down. The pulsar within the X-ray binary SXP 1062 (figure 5) could potentially result from this process; its 1062 s rotational period is entirely unexpected given its youth (~10–40 kyr, from the SN remnant; Hénault-Brunet *et al.* 2012).

Considered as a whole, these developments indicate that our census of magnetars and potential progenitors in our galaxy is incomplete, although we are not yet ready to ascertain by what degree; hence we cannot assess whether the fossil-field and/or dynamo hypothesis is excluded.

## Progenitor histories

An alternative approach is to infer formation channels from the properties of the environment in which magnetars formed. Several variations on this theme are possible. Gaensler *et al.* (2005) analysed the bubble of material surrounding the magnetar 1E 1048.1-5937, interpreting it as a windblown shell from a 30–40 $M_\odot$ progenitor. Abundance studies of the supernova remnant Kes 73 (figure 3) surrounding 1E 1841-045 indicate a ~20 $M_\odot$ progenitor; similar conclusions are drawn for the high-**B**-field pulsar J1119-6127 (Kumar *et al.* 2014).

A more direct approach is possible for the four magnetars which are found to be spatially coincident with young massive clusters. Here progenitor masses may be inferred from the properties of the most evolved cluster members present, since the lifetime of the active magnetar phase is expected to be short in comparison to the stellar evolutionary timescale. In the eponymous clusters associated with SGR 1806-20 and SGR 1900+14 (figure 6) this implies progenitor masses of $48^{+20}_{-8}$ $M_\odot$ (Bibby *et al.* 2008) and $17^{+2}_{-2}$ $M_\odot$ (Davies *et al.* 2009) respectively. These estimates rely on comparison of current stellar properties to evolutionary calculations and so must be treated with caution. However, we may circumvent this uncertainty for the magnetars within Westerlund 1 (Wd 1; Muno *et al.* 2006;




**6** Multiple-epoch high spatial resolution imaging observations of SGR 1806-20 (left) and SGR 1900+14 (right) by Tendulkar *et al.* (2012) permit their proper motion to be measured. The blue diamonds mark their current locations, while the solid red lines and ellipses represent the angular uncertainty in their proper motion and the resultant positional uncertainty, respectively, when their motions are traced back by ~0.65 kyr (SGR 1806-20) and ~6 kyr (SGR 1900+14). Clearly, both magnetars could have originated in the nearby clusters (with the dashed blue circles representing their nominal extent).

figure 4) and the circumnuclear cluster in our galaxy (Mori *et al.* 2013) because both contain eclipsing binaries from which kinematic masses may be determined. This leads to minimum progenitor masses of ~35 $M_\odot$ (Ritchie *et al.* 2010) and, from Martins *et al.* (2006), ~50 $M_\odot$ respectively.

What conclusions may be drawn from these findings? First, magnetars appear to form from stars with a wide range of masses (~17 $M_\odot$ to >50 $M_\odot$). Secondly, taken at face value they suggest that stars ranging from ~8–17 $M_\odot$, which are known to experience core-collapse supernovae and are far more numerous (from the shape of the stellar initial mass function), are unable to form magnetars. While this conclusion may be valid, it is important to note (i) the small number of sources currently considered and (ii) that young clusters rapidly dissolve as they age, making them progressively harder to detect against field stars. As a result we might expect to preferentially detect magnetars associated with very young clusters hosting very massive stars.

Finally, magnetars are found in clusters where, given the very high masses of the constituent stars, black holes might instead be expected to form. A solution to this apparent paradox is to invoke binarity. In compact systems of two massive stars, mass transfer from the primary will strip away its H-rich outer layers, exposing the chemically evolved core earlier than otherwise expected. Subsequently, the powerful stellar winds of the core (a Wolf-Rayet star) reduce its mass to the point at which a neutron star rather than a black hole will form. Such a pathway has the additional benefit that it prevents a supergiant phase in which core–envelope coupling can cause the spin-down that would prevent magnetar formation via the dynamo channel.

Recent observations of the stellar population of Wd 1 seem to confirm this scenario, identifying a high-velocity runaway star – Wd 1-5 – escaping from the cluster (figure 4, lower panel). An obvious explanation is that it was ejected during the supernova event that formed the magnetar; analysis of its spectrum reveals a carbon-enhanced chemistry that can only have arisen via binary evolution. We may employ the current properties of Wd1-5 to infer a pre-supernova history for the putative Wd 1 magnetar progenitor system (Clark *et al.* 2014): a compact 41 $M_\odot$ + 35 $M_\odot$ binary (period <8 days) begins to interact as the primary runs out of fuel, transferring its outer layers to its less massive companion – destined to become the magnetar – causing it to rapidly spin-up. As a result of this mass transfer, the secondary becomes so massive that it evolves more rapidly than the primary, initiating a second interactive phase in which its outer layers are also ejected, revealing the chemically processed core. A final phase of mass transfer from this pollutes the primary, yielding its anomalous chemistry, before the secondary is lost to a Type Ibc SN which unbinds the binary and forms the magnetar.

**"After 40 years there is no consensus: what is the nature of the central engine?"**

It is important to note that Wd 1 hosts a rich binary population which contains exact analogues of the system outlined above, such as the massive, short-period binary Wd 1-44, comprising a blue hypergiant (the Wd 1-5 equivalent) and O supergiant (the putative magnetar progenitor; Clark *et al.* 2014). Therefore, observational precedents for this scenario exist and indeed suggest the potential for additional magnetar formation within Wd 1.

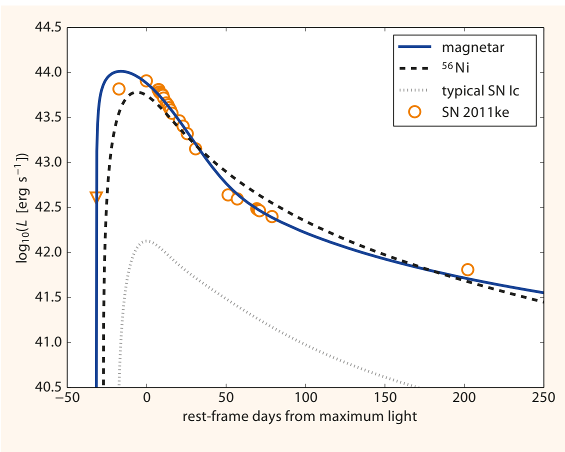
Additionally, the pathway sketched above yields a progenitor which has been spun-up to critical rotation and subsequently had its outer layers stripped away, limiting the possibility for spin-down prior to supernova, satisfying one criterion for the dynamo formation channel to operate. Moreover, the binary interactions could be expected to induce a magnetic field in the progenitor that, depending on its strength, could provide the seed field required for a dynamo to operate in the proto-neutron star, or even be strong enough to satisfy the requirements of the fossil-field scenario (Clark *et al.* 2014, Langer 2013).

## Magnetars and high-energy events

Given these uncertainties, why expend so much effort in order to understand the origin of magnetars? To answer this we must return to the cosmological GRBs with which they were first confused. Despite the more than 40 years since their discovery, there remains no consensus on the most fundamental question: what is the nature of the central engine that powers them? Under the well-known "collapsar" model (Woosley 1993) the energy for GRBs is supplied by matter from a thick torus accreting onto a newly formed black hole. Recently, however, the proposal of Usov (1992) that "millisecond pulsars with extremely strong magnetic fields" – aka magnetars – could drive GRBs has received increased attention. Indeed, Woosley (2010), Kasen & Bildsten (2010) and Metzger *et al.* (2011) suggest that they could also explain superluminous supernovae (SLSNe) and related high-energy and/or luminosity transients.

This is made possible by a hitherto neglected energy source: rotation. The rotational energy of a typical neutron star is approximated by $2 \times 10^{52} (P_{ms})^{-2}$ erg (with the period in ms); potentially a huge reservoir to draw upon, given the rotational velocities predicted at birth for protomagnetars under the dynamo hypothesis. Moreover, the presence of an extreme **B**-field provides the key to unlock this potential, with the energy loss via dipole radiation approximated by $\sim 10^{49} (\boldsymbol{B}_{15})^2 (P_{ms})^{-4}$ erg s$^{-1}$ (where $\boldsymbol{B}$ is in units of $10^{15}$ G; Woosley 2010). So not only does the energy budget of rapidly rotating magnetars suffice to produce both GRBs and SLSNe, but it may be extracted on the requisite short timescales. Conversely, the fossil-field channel does not require rapid rotation – and even disfavours it due to magnetic core-envelope coupling. Consequently this energy source is not available to be tapped.

It is then of paramount interest to determine if the dynamo formation channel is




**7** The bolometric light curve of SN 2011ke, compared with magnetar- and $^{56}$Ni-powered models. The magnetar, inside 6.7 $M_\odot$ of ejected SN material, has a spin period of 1.7 ms and a **B**-field of $6.4\times10^{14}$ G. The $^{56}$Ni model shown has 8 $M_\odot$ of ejecta, along with an extreme kinetic energy ($3\times10^{52}$ erg) and unprecedented nickel mass (3.75 $M_\odot$). For comparison, a model for a normal Type Ic SN is also shown, with 2 $M_\odot$ ejecta, 0.07 $M_\odot$ $^{56}$Ni, and kinetic energy of $10^{51}$ erg. (Adapted from Nicholl *et al.* 2014 and Inserra *et al.* 2013)

indeed viable and hence whether magnetars can function as the central engine of the growing menagerie of cosmological explosions. Consequently, despite the complexity of the physics, much effort is being expended in developing quantitative observational predictions for both GRBs (Metzger *et al.* 2011) and SLSNe (Nicholl *et al.* 2014) powered by magnetars. Initial results have been encouraging; figure 7 presents a comparison of the lightcurve of the SLSN 2011ke to models powered by both magnetars and $^{56}$Ni, showing a significantly better fit for the former, even if an unfeasibly large quantity of nickel is assumed to form under the latter scenario.

But we caution that evidence for such highly energetic, magnetar-powered supernovae and GRBs in the local universe is sparse. We know that magnetars readily form in metal-rich galaxies such as our own, but given the observed paucity of GRBs and SLSNe in these environments it seems implausible to assume that the birth of all magnetars are associated with their production (indeed, to date all SLSNe have been found in metal-poor dwarf galaxies; e.g. Lunnan 2013). A subset of magnetars are found to be associated with supernova remnants, which one might expect to systematically differ from the wider population if excess energy has been deposited within them, but to date no evidence has been found in the four objects so studied (Vink 2008 Martin *et al.* 2014 and in figure 3). Given the small sample, this is not yet conclusive and one could suppose that rotational energy was instead lost as gravitational energy or by driving a relativistic jet.

An additional prediction of the dynamo mechanism is that it may result in the magnetar receiving a large "kick" during formation. If the optical or radio counterpart to a magnetar were to be identified, proper-motion studies could yield a kinematical velocity to test this hypothesis. To date this has been accomplished for six magnetars; Tendulkar *et al.* (2013) showed that their mean velocity is in excellent agreement with that of the wider pulsar population, contrary to this forecast. One magnetar, SGR 0526-66, may buck this trend; if its physical association with the supernova remnant N49 is confirmed, its location on the limb of the remnant (figure 3) would imply a transverse velocity of $\sim10^3\ \mathrm{km\,s^{-1}}$, as predicted by Duncan & Thompson (1992).

## Future perspectives

It is important to recall just how revolutionary the idea that neutron stars could be powered by magnetism was in 1992; however, subsequent observations have provided a compelling case that magnetars do indeed host the strongest magnetic fields in the universe. Despite observational and theoretical progress, the physical process that transforms energy stored in the **B**-fields of magnetars into X-ray and gamma-ray emission remain frustratingly opaque. Additional detections and a better understanding of the duty cycle of magnetars offered by an increasing temporal baseline of observations should address this and, in particular, the processes leading to spectacular giant flares. Such data will also better constrain the galactic population of magnetars, a critical measurement if we are to understand their origin.

Given the possibility that magnetars form the central engines of both GRBs and SLSNe, a fuller understanding of their production mechanism – dynamo versus fossil-field – is of obvious importance. Indeed, if nature permits both rapidly rotating and highly magnetic supernova progenitors, there is no *a priori* reason why both channels should not be viable. Note, however, that if magnetars do not power GRBs, then rapidly rotating cores before supernova are still required under the collapsar scenario. It is therefore of particular interest that current observations suggest that binarity is an important ingredient in magnetar formation, with interaction between the components yielding conditions that favour the production of rapid stellar rotation and potentially the generation of strong **B**-fields in supernova precursors.

It is to be hoped that a combination of large statistical studies and tailored analysis of individual systems will drive progress. A necessary corollary is that current constraints on formation mechanism are derived from the local universe, and not the high-redshift environment in which GRBs and SLSNe preferentially (exclusively?) occur. Low metallicity may affect stellar evolution, favouring the production of rapidly rotating pre-supernova stellar cores. Indeed, given the recurring role of rotation in this topic, it is perhaps appropriate that the story of magnetars can now be seen as a circular one in which, having first been confused with GRBs of cosmological origin, they are now centre stage in understanding the physical processes powering these enigmatic events. ●

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