Triggers of magnetar outbursts

Robert C. Duncan
University of Texas at Austin  TX  USA

Abstract. Bright outbursts from Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) are believed to be caused by instabilities in ultramagnetized neutron stars, powered by a decaying magnetic field. It was originally thought that these outbursts were due to reconnection instabilities in the magnetosphere, reached via slow evolution of magnetic footpoints anchored in the crust. Later models considered sudden shifts in the crust’s structure. Recent observations of magnetars give evidence that at least some outburst episodes involve rearrangements and/or energy releases within the star. We suggest that bursting episodes in magnetars are episodes of rapid plastic yielding in the crust, which trigger “swarms” of reconnection instabilities in the magnetosphere. Magnetic energy always dominates; elastic energy released within the crust does not generate strong enough Alfvén waves to power outbursts. We discuss the physics of SGR giant flares, and describe recent observations which give useful constraints and clues.

1. Introduction: A neutron star’s crust

The crust of a neutron star has several components: (1) a Fermi sea of relativistic electrons, which provides most of the pressure in the outer layers; (2) another Fermi sea of neutrons in a pairing-superfluid state, present only at depths below the “neutron drip” level where the mass-density exceeds $\rho_{\text{drip}} \approx 4.6 \times 10^{11} \text{ gm cm}^{-3}$; and (3) an array of positively-charged nuclei, arranged in a solid (but probably not regular crystalline) lattice-like structure throughout much of the crust. These nuclei become heavier and more neutron-bloated at increasing depths beneath the surface, until the swollen nuclei nearly “touch” and the quasi-body-centered-cubic nuclear array dissolves into rod-like and slab-like structures near the base of the crust: “nuclear spaghetti and lasagna” or “nuclear pasta” (e.g., Pethick & Ravenhall 1995).

In a magnetar, the crust is subject to strong, evolving magnetic stresses. Magnetic evolution within the crust occurs via Hall drift; while ambipolar diffusion and Hall drift of magnetic flux within the liquid interior strains the crust from below (Goldreich & Reisenegger 1992; Thompson & Duncan 1996, hereafter “TD96”). The crust and the magnetic field thus evolve together through a sequence of equilibrium states in which magnetic stresses are balanced by material restoring forces. Because a magnetar’s field is so strong, this evolution inevitably involves episodes of crust failure driven by the magnetic field on a variety of time-scales. Many complexities
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are likely to affect the crustal yielding threshold, and cause it to vary from place to place within a neutron star’s crust. Moreover the very nature of neutron star crust failure is somewhat uncertain. In the deep crusts of magnetars, yields may resemble sudden and sporadic flow in an inhomogeneous liquid crystal, induced by evolving magnetic stresses.

Before discussing these complications, it is worthwhile to note how neutron star crust material, outside the pasta layers, differs from a terrestrial solid. A key difference (due to the high mass-density in a neutron star) is that the relativistic Fermi sea of electrons is only slightly perturbed by the Coulomb forces of the nuclei, and does not efficiently screen nuclear charges. With a nearly inert and uniform distribution of negative charge, pure neutron star crust-matter comes close to realizing the “ideal Coulomb crystal.” Such a body-centered cubic (bcc) lattice is expected to form in the low-temperature limit of a “one-component plasma” (e.g., Brush, Sahlin & Teller 1966; Ichimaru 1982; van Horn 1991). The crystallization temperature is

\[ k_B T_c = \Gamma^{-1} (Ze)^2 / a, \]

where \( Z \) is the ionic charge, \( a \) is the Wigner-Seitz radius satisfying \( \frac{4}{3} \pi a^3 = n^{-1} \) with ion density \( n \), and \( \Gamma \) is a numerical constant found in statistical mechanics to be \( \Gamma \approx 170 \). In the deep crust of a neutron star, \( T_c \sim 10^{10} \) K.

The electrostatic structure of naturally-occurring terrestrial solids is more complex, with bound electrons and efficient screening. Only in the cores of old white dwarfs, which have cooled sufficiently to crystallize, does bulk material like the stuff of a neutron star’s outer crust \( (\rho < \rho_{\text{drip}}) \) exist elsewhere in nature. Inner-crust matter is found nowhere outside of neutron stars.

However, nearly-ideal Coulomb crystals have recently been made in the laboratory, and the failure of these crystals under stress was studied (Mitchell et al 2001). I will now describe one of these delicate and elegant experiments.

About 15,000 cold \(^9\text{Be}^+\) ions were confined within a volume about half a millimeter in diameter, in the laboratory at the National Institute of Standards in Boulder, Colorado. A uniform magnetic field confined the ions radially, while a static electric field with a quadratic potential trapped them axially (i.e., a Penning trap). The ions were cooled to millikelvin temperatures using lasers that were tuned to a frequency just below an ionic ground-state excitation level. The plasma crystallized into a disk, with a bcc lattice structure. (Note that trapping fields effectively provided the neutralizing background for this crystal.) Due to a weak radial component of the electric field, the charged crystal experienced \( E \times B \) drift and rotated. The velocity of rotation was controlled and stabilized by the experimenters using a perturbing electric field. The ions, fluorescing in laser light and separated by 15 microns, were directly imaged and photographed. The crystal was then stressed by illuminating it with laser light from the side, and off-axis. Slips in the crystalline structure were detected. They were distributed, over at least three orders of magnitude, according to a power law with index between 1.8 and 1.2.

One can’t avoid mentioning here that this distribution of slip sizes resembles the energy-distribution of bursts from SGRs. Some would claim that this is a consequence of “universality” in self-organized critical systems. In any case it can have no deep implications about burst mechanisms, since the physics of SGR outbursts is much more complex than simple slips in a crystal.

These experiments verify some expectations about idealized, crystalline neutron
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star matter; but real neutron star crusts, and especially magnetar crusts, are likely to be complex and messy. As emphasized by Ruderman (1991), the circumference of a neutron star is about \(10^{17}\) lattice-spacings, which is similar to the size of the Earth measured in the lattice-spacings of terrestrial rock.

According to the old, 20th century neutron star theory, the amount and distribution of crystalline imperfections in the crust is history-dependent. Two factors were thought to be involved: the rapidity of cooling when the solid originally formed, and the subsequent “working” of the solid by stresses and (in some cases) episodic re-heating. More rapid initial cooling and solidification would generally produce more lattice imperfections and smaller lattice domains (i.e., smaller grains). Extremely rapid cooling, or “quenching” would produce an amorphous (glassy) solid rather than a crystal, which is really a long-lived metastable state: a super-cooled liquid. It was suggested that this occurs in neutron star crusts (Ichimaru et al. 1983); however, models of crust solidification in more realistic, neutrino-cooled neutron stars showed crystallization (de Blasio 1995). Subsequent strain-working of the crust would increase lattice imperfections, while episodes of (magnetic) re-heating followed by cooling would tend to anneal the solid.

That’s the old picture. Jones (1999, 2001) recently turned the story on its head. He showed that, when the crust initially cools through the melting temperature, a substantial range of Z (i.e., nuclear proton-numbers) get frozen-in at every depth below neutron drip. This is due to thermal fluctuations in the nuclei, which are in equilibrium with the neutron bath. The energy separation of magic-number proton shells in the neutron-bloated nuclei is not large compared to the melt temperature. This is important because it means that the crust of a 21st-century neutron star is amorphous rather than crystalline. There exists some short-range crystalline order, but over distances greater than about \(\sim 10\) a the variable Z’s affect the inter-nuclear spacing enough to destroy all order. This has important implications for transport properties such as electrical conductivity, among other things.

Finally, there is the sticky issue of nuclear pasta (Pethick & Ravenhall 1995 and references therein).∗ Deep inside the crust, the neutron-bloated nuclei become elongated and join into “nuclear spaghetti”: long cylindrical structures in a 2-D triangular array. As depth and density increase, these nuclear noodles join into slabs: “nuclear lasagna.” At even higher densities this gives way (at least for some values of nuclear state parameters) to “inverse spaghetti”: an array of cylindrical holes in the high-density fluid; followed by “inverse meatballs”: a bcc lattice of spherical holes in otherwise continuous nuclear matter. Beneath that lies continuous nuclear fluid.

Because rod-like (or planar) structures can freely slide past each other along their length (and breadth) without affecting the Coulomb energy, nuclear pasta has an extremely anisotropic tensor of elasticity. Indeed, the elastic response of nuclear spaghetti resembles that of the columnar phases of a liquid crystal, and elastic nuclear lasagna resembles the smectics A phase (Pethick & Potekhin 1998). At sufficiently

∗ Nuclear pasta results from the competition between Coulomb and nuclear surface-energy terms when minimizing the energy. The pasta ground states exhibit spontaneously broken symmetries, although the underlying interactions between constituent nucleons are nearly rotationally-symmetric. This is different from the case with terrestrial liquid crystals, in which highly-anisotropic inter-atomic forces give rise to the broken global symmetries.
high temperatures, positionally-disordered \textit{(nematic)} phases are also possible; but the threshold for this is $\sim 10^{10}$ K.

It has been suggested that up to half the mass of a neutron star’s crust is in nuclear pasta (Pethick & Potekhin 1998). A detailed, realistic understanding of the response of a neutron star’s crust to evolving stresses (especially stresses largely exerted from below by a magnetic field, as likely in a magnetar) may require understanding the size and coherence of nuclear pasta domains; their orientation relative to the vertical; the interactions of pasta with the magnetic field; and the yielding behavior of such liquid crystals, which plausibly depends upon instabilities in the pasta domain structure. These difficult issues have not begun to be addressed by astrophysicists.

Thus the range of complicating factors which could affect neutron star crust evolution is formidable. In the case of a magnetar, the crust is coupled to an evolving ultra-strong magnetic field and its generating currents, which penetrate the underlying core as well. Manifold uncertainties about field geometries and magnetic evolution compound the murkiness. Observations of SGRs and AXPs could provide the most sensitive probes of neutron star interiors available to astronomers, because magnetars are much less stable than other neutron stars. However, the intertwined complexities of neutron star magnetic activity must be unraveled.

In this review we focus on one aspect of this problem: the triggering of bright outbursts. We will try to keep the discussion on a basic physical level, eschewing equations as much as possible. In Section 2 we review the physics and phenomenology of SGR outbursts. In Section 3 we compare rise-time observations with models for trigger mechanisms. Section 4 discusses other observations which offer clues. Section 5 discusses the general issue of crust-failure in magnetars. Section 6 gives conclusions.

1.2 Magnetar outbursts: a brief review

“Flares are triggered in magnetically-active main-sequence stars when convective motions displace the footpoints of the field sufficiently to create tangential discontinuities, which undergo catastrophic reconnection. Similar reconnection events probably occur in magnetars, where the footpoint motions are driven by a variety of diffusive processes.” - Duncan & Thompson (1992)

This quotation shows that magnetar outbursts were originally conceived as being triggered in the magnetosphere, as a consequence of the neutron star’s slow, interior magnetic evolution. This was believed to apply to giant flares as well: “The field of a magnetar carries sufficient energy to power the 1979 March 5th event (5 \times 10^{44} \text{ ergs at the distance of the LMC, assuming isotropic emission; Mazets et al. 1979}).” (DT92)

Note that the March 5th event was the only giant flare which had been detected at that time, with energy $> 200$ times greater than the second most-energetic SGR event.

Paczyński (1992), in work done soon after DT92, made this point more explicitly. He suggested that the March 5th event was “caused by a strong magnetic flare at low optical depth, which led to a thermalized fireball...”

By 1995, Thompson and I had realized that the evolving, strong field of a magnetar was capable of straining the crust more severely than it could bear. Thompson & Duncan 1995 thus discussed the relative merits of impulsive crustal shifts and
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pure magnetospheric instabilities as outburst triggers. TD95 favored scenarios in which both processes occurred, with the 1979 March 5th event involving profound exterior reconnection. Thompson & Duncan 1995 and 1996 also discussed plastic deformation of magnetar crusts. Besides high plasticity at places where the temperature approaches $\sim 0.1 T_c$ (plausibly due to local magnetic heating), we noted that magnetic stresses dominate elastic stresses if $B > B_\mu = (4\pi\mu)^{1/2} = 4 \times 10^{15} \rho_{14}^{0.4} \text{ G}$, where $\mu$ is the shear modulus, and $\rho_{14}$ is the mass-density in units of $10^{14} \text{ gm cm}^{-3}$. A magnetic field stronger than $B_\mu$ is thus like a 600-pound gorilla: “it does whatever it wants” in the crust. We noted possible implications of plastic deformation for glitches, X-ray light curve variations, and triggering catastrophic reconnection (TD95; TD96; Thompson et al. 2000; TD01).

Observations made after 1996 have tended to fill in the “energy gap” between the 1979 March 5th event and other SGR outbursts. In particular, the 1998 August 27th giant flare was about $10^{-1}$ times as energetic as the March 5th event (Hurley et al. 1999a; Mazets et al. 1999a; Feroci et al. 1999); and two intermediate-energy events† have been observed: the 2001 April 18 flare from SGR 1900+14 (Kouveliotou et al. 2001; Guidorzi et al. 2003) and the slow-rising 1998 June 18 flare from SGR 1627-41 (Mazets et al. 1999b) which had no long-duration, oscillating soft tail. The emerging continuity in outburst energies makes it more plausible that giant flares and common SGR bursts differ in degree rather than in kind; while the profound differences between outbursts of comparable energies indicate that a wide variety of physical conditions and processes are involved.

Studies of SGR burst statistics since 1996 have also yielded important insights. Cheng, Epstein, Guyer & Young (1996) noted that the statistical distribution of SGR burst energies is a power law with index 1.6, resembling the Gutenberg-Richter law for earthquakes. Such a distribution can result from self-organized criticality (Katz 1986; Chen, Bak & Obukhov 1991). Cheng et al. found additional statistical resemblances between SGR bursts and earthquakes, as verified and further studied by Göğüş et al. (1999 and 2000) with a much larger sample of SGR events. AXP 2259+586’s June 2002 active episode showed very similar burst statistics (Gavriil, Kaspi & Woods 2003). These results lend support to the hypothesis that SGR/AXP outbursts are powered by an intrinsic stellar energy source, which is plausibly magnetic. (Accretion-induced events, including Type I and Type II X-ray bursts, have much different statistics.) However, as Göğüş et al. pointed out, these burst statistics do not necessarily argue that SGR bursts are crustquakes. Similar statistical distributions have been found in solar flares (Crosby, Aschwanden & Dennis 1993; Lu et al. 1993).

In 2001, Thompson and I studied an idealized “toy model” for a giant flare. In this model, a circular patch of crust facilitates the release of magnetic energy by yielding along circular fault and twisting. Circular crust displacements are plausible because the crust is stably-stratified and strongly constrained in its motion, yet significant twisting movement could be driven by the magnetic field. Moreover, a magnetar’s

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* Here, I call intermediate-energy events flares but not giant flares. Events releasing $\sim 10^{41} \text{ ergs}$ or less are traditionally called bursts. I use outburst as a generic term for all magnetar events.
† The common, 0.1 s SGR bursts, on the other hand, “could be driven by a more localized and plastic deformation of the crust.” (TD01)
formation as a rapid rotator should significantly “wind up” the star’s interior field (DT92); and twists of the exterior field, which would result from this kind of magnetic activity, could drive currents through the magnetosphere, contributing to the observed, quiescent X-ray emissions from magnetars (Thompson et al. 2000).

Note that the crust-yielding event in a giant flare, if it occurs, is not a brittle fracture. Neutron star crusts probably undergo plastic failure, at least outside the nuclear pasta (Jones 2003). The sudden yielding event could have been a widely-distributed plastic flow along circular flow-lines induced by rapidly-changing stresses exerted by the core field from below.

Alternatively, there may exist instabilities within the crust that cause rapid mechanical failure, triggering giant flares (and/or other events). The failure of nuclear pasta could involve sudden instabilities due to the interactions of domains with differently-oriented, strongly anisotropic elastic/liquid response. In the solid crust, a sufficiently long and localized plastic slip could drive melting along the fault, suppressing the normal elastic stress and mimicking a brittle fracture. Jones (2003) estimates that this could occur for slips longer than a few centimeters. The process might be facilitated, as a “mock-fracture” propagates, by the development of magnetic gradients within the fault plane, with localized magnetic heating.

In 2002, Thompson, Lyutikov & Kulkarni (hereafter “TLK”) considered the possibility that giant flares are instabilities which develop in the magnetosphere with no energetically-significant crust displacement on the time-scale of the flare. Section 5.6 of TLK discussed four pieces of observational evidence which bear on the question of which mechanism operates. TLK argued that three out of four favored crust-yielding. Finally, Lyutikov (2003) gave a new estimate of the rise-time for magnetospheric instabilities in magnetars. Since rise times are an important diagnostic we now discuss them in detail.

1.3 Outburst rise-times and durations

There are two rise-times of interest in SGR outbursts: the “growth time” $\tau_{grow}$ which is the e-folding time for the energy-flux growth during the initial, rapid brightening; and the “peak time” $\tau_{peak}$ which is the time from the initial onset of the event until the (highest) peak of the light curve.

A third time-scale of interest in the brightest SGR events is $\tau_{spike}$, the duration of the initial, hard-spectrum, extremely bright phase of the event which we refer to as the “hard spike.” In both giant flares on record, this spike is followed by an intense “soft tail” of X-rays, modulated on the rotation period of the star. The soft tail is thought to be emitted by an optically-thick “trapped fireball” in the magnetosphere of a magnetar (TD95). The abrupt vanishing of soft tail emission at the end of the 1998 August 27th event seems to be due to fireball evaporation, corroborating this interpretation (Feroci et al. 2000; TD01).

The March 5th 1979 event reached its peak at $\tau_{peak} \approx 20$ ms, but the initial, fast rise through many orders of magnitude was unresolved by ISEE or the Pioneer Venus Orbiter, thus $\tau_{grow} < 0.2$ ms (Cline et al. 1980, Terrel et al. 1980; Cline 1982). The initial, hard-spectrum emission lasted for $\tau_{spike} \sim 0.15$ s (Mazets et al. 1979), during which time it showed variability on timescales of order $\sim 10 - 30$ ms (Barat et al. 1983).
1.3 Outburst rise-times and durations

Thompson and I suggested interpretations of these time scales. TD95 noted (in eq. 16) that the Alfvén crossing time within the (fully-relativistic) magnetosphere of a magnetar is comparable to the light-crossing time of the star, roughly 30 microseconds. “Since reconnection typically occurs at a fraction of the Alfvén velocity, the growth time of the instability is estimated to be an order of magnitude larger... This is, indeed, comparable to the 0.2 msec rise time of the March 5 event.” In other words, we suggested

\[ \tau_{\text{grow}} \sim \frac{L}{0.1V_A} \sim 0.3 \left( \frac{L}{10 \text{ km}} \right) \text{ ms}, \quad (1.1) \]

where \( L \) is the scale of the reconnection-unstable zone, and \( V_A \sim c \) is the (exterior) Alfvén velocity. (Observations of solar flares give evidence that reconnection often proceeds at speeds \( \sim 0.1 V_A \); e.g. Dere 1996.) TD95 further suggested that \( \tau_{\text{spike}} \) is comparable to the interior Alfvén wave crossing time of the star, which applies if the event involves an interior magnetic rearrangement. This yields

\[ \tau_{\text{spike}} \sim 0.1 B_{15}^{-1} \rho_{15}^{-0.1} (\Delta \ell/R_\star) \text{ s} \ [\text{TD95 eq. 17}], \]

in agreement with giant flare data:

\[ \tau_{\text{spike}} = 0.15 \text{ s} \ [\text{March 5th event}] \text{ and } 0.35 \text{ s} \ [\text{August 27th event}]. \]

Another physical time scale of possible relevance is the shear-wave crossing time of the active region of crust. (This is the elastic stress-equilibration timescale even when the generation of propagating shear waves is small.) The shear-wave velocity \( V_{\mu} = (\mu/\rho)^{1/2} \) is insensitive to depth (or local density \( \rho \)) in the crust, at least in the zones outside the nuclear pasta: \( V_{\mu} = 1.0 \times 10^3 \rho_{14}^{-0.1} \text{ km s}^{-1} \ [\text{TD01, eq. 8}]. \) For an active region of size \( \ell \), this gives a crossing time \( \tau_{\mu} = \ell/V_{\mu} = 3 (\ell/3 \text{ km}) \text{ ms} \) (TD95), thus \( \tau_{\text{grow}} \leq \tau_{\mu} \leq \tau_{\text{peak}} \) for the March 5th flare.

The light curves of common, repeat bursts from SGRs were studied by Göğüş et al. (2001), using a data-base of more than 900 bursts from two SGRs that were observed using the Rossi X-ray Timing Explorer (RXTE). Göğüş et al. found that the distribution of burst durations (as measured by \( T_{90} \), the time in which 90% of the burst counts accumulate) is lognormal, with a peak of order 100 ms. Most bursts rise faster than they decline, but many have roughly triangular light curves. In particular, about half of all bursts have \( \tau_{\text{peak}} > 0.3 T_{90} \). Thus the distribution of \( \tau_{\text{peak}} \) peaks at \( \sim \) 30 ms, and \( \tau_{\text{grow}} \) peaks around \( \sim 10 \text{ ms} \).

Lyutikov (2003) studied the growth of spontaneous reconnection in magnetar magnetospheres. Compared to better-understood conditions in the Solar chromosphere, radiative cyclotron decay times are extremely short, forcing currents to flow narrowly along field lines. The plasma is thus force-free and relativistic, being dominated by the magnetic field. Lyutikov suggested that a tearing-mode instability operates within current-sheets, involving the clustering of current filaments within the sheet and the formation of “magnetic islands.” This has a rate \( \tau_{\text{rise}} \sim \sqrt{\tau_{A_{\text{ur}}}} \), just as in the non-relativistic case, where \( \tau_A \sim \ell/c \) is the Alfvén crossing time of the unstable zone, and \( \tau_{A_{\text{ur}}} \) is the resistive time-scale \( \tau_{R_{\text{r}}} \sim \ell^2/\eta \). Lyutikov conjectured that either Langmuir turbulence or ion sound turbulence provide the resistivity: \( \eta \sim c^2/\omega_p \), where \( \omega_p \) is the (electron or ion) plasma frequency. To evaluate this requires an
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estimate of the local particle density. Lyutikov adopted a value expected in the “globally-twisted magnetosphere” model of TLK, which yields

\[ \tau_{\text{grow}} \sim 0.1 \left( \frac{L}{10 \text{ km}} \right)^{3/2} \left( \frac{r}{100 \text{ km}} \right)^{-7/8} \left( \frac{B_{\text{pole}}}{5 \times 10^{14} \text{ G}} \right)^{1/4} \text{s}, \]  

(1.2)

for Langmuir turbulence, or smaller by a factor \((m_p/m_e)^{1/4} = 6.5\) for ion sound turbulence. If reliable, this analysis represents an improvement over TD95’s crude estimate [eq. (1) above]. But to match observed rise-times requires quite localized events, high in the magnetosphere, with fully-developed ion turbulence in the tearing layer. If the events happen closer to the stellar surface \((r \sim 10 \text{ km})\) as likely,∗ then the rise time is closer to \(\sim 1 \text{ s}\) for electron turbulence and \(\sim 0.1 \text{ s}\) for ions. The problem is that this mechanism requires low particle densities \(n\) to proceed quickly:

\[ \tau_{\text{grow}} \propto \omega_{\text{p}}^{1/2} \propto n^{1/4}. \]

More realistic models of the magnetosphere than a simple global twist will greatly exacerbate the discrepancy, because reconnection occurs where the current density \(j\) (and thus \(n \sim [j/qv]\), where \(q\) is the charge and usually \(v \sim c\)) is especially large, in current sheets. That is, the magnetosphere can be locally as well as globally twisted; and the current density is determined by local magnetic shear.

Other mechanisms besides tearing modes coupled to ion sound turbulence probably operate in nonrelativistic astrophysical reconnection, and seem worthy of investigation in the magnetar context. One possibility is stochastic reconnection (Lazarian & Vishniac 1999), which requires some source of turbulence on scales that are larger than the current sheet width. In a magnetar this might be provided by crust-yielding motion which agitates the field near a developing magnetic discontinuity.

1.4 Other observational clues

There is evidence that at least some magnetar outbursts involve structural adjustments inside the star, with enhancements of magnetospheric currents:

- The 1998 June 18 event from SGR 1627-41 resembled a slow-rising giant flare with no soft tail (Mazets et al. 1999b). One plausible interpretation is that the star experienced a deep stellar adjustment that triggered little exterior reconnection or other energy dissipation in zones of low-lying, closed field-lines (relative to other powerful flares) and thus no long-lasting trapped fireball. This is consistent with the results of Kouveliotou et al. (2003), who studied X-ray emissions from SGR 1627-41 following June 1998. For two years, the light curve was a 0.47-index power law, gradually leveling off to a “plateau”; and then, after 1000 days, dropping precipitously. Kouveliotou et al. found that the cooling crust of a \(10^{15}\) Gauss neutron star could follow this pattern if the initial energy deposition (presumably on June 18th)

∗ Note that the electron plasma frequency is approximately \(\omega_{\text{p}} \sim \sqrt{\omega_{B} c/r} \sim 3 \times 10^{11} \text{ rad/s}\), where the cyclotron frequency \(\omega_{B} = (eB/mc)\) is evaluated at \(r = 100 \text{ km}\), outside a \(R = 10 \text{ km}\) star with polar field \(B_{\text{pole}} = 5 \times 10^{14} \text{ Gauss}\), assuming \(B(r) = B_{\text{pole}}(r/R)^{-2-p}\) with \(p = 1/2\) in a strongly twisted magnetosphere, \(\Delta \phi \approx 2 \text{ radians}\).

∗ The fraction of exterior magnetic energy lying beyond radius \(r\), \(f_B(r) > r\) falls off substantially faster than the pure dipole contribution, \(f_B(r) = (r/R)^{-1-2p}\), where \(p = 1/2\) for no global twist. So the fraction of energy available for reconnection at \(r > 100 \text{ km}\) is significantly less than \(10^{-2}\) [\(p = 1/2\); 2-rad twist] or \(10^{-3}\) [untwisted].
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extended deep into the crust, significantly below neutron drip. The integrated energy of the X-ray afterglow was comparable to the June 18 outburst energy; but the impulsive energy injection in the crust had to be much larger (by a factor $\sim 10^2$ in Kouveliotou et al.’s models) because of deep conduction and neutrino losses. This would then be a (relatively) crust-active, magnetosphere-quiet magnetar. One concern with this interpretation is that the observed afterglow spectrum was non-thermal and time-variable. It has not yet been shown that reprocessing by scattering in the magnetosphere can (fully) account for this. Other interpretations of SGR 1627-41 data might still be possible.

- The June 18 event had a total duration $\Delta t \sim 0.5$ s, comparable to a magnetar’s internal Alfvén-crossing time (cf. TD95). This flare also peaked much more gradually than other flares: $\tau_{\text{peak}} \sim 0.1$ s. This could be consistent with slow, catastrophic crust failure, say at a rate $V \sim 0.1V_\mu$, along a large fault-line or plastic shear-zone: $\tau_{\text{peak}} \sim 0.1(\ell/10 \text{ km})$ s (Mazets et al. 1999b). Note that a zone of crust adjusting over a timescale $\tau \gtrsim 0.1$ s would produce little Alfvén wave emission on field lines shorter than $c \cdot \tau \sim 3 \times 10^4$ km. If the energy of this flare was released mostly on far-reaching field lines, then it would tend to blow these field lines open where the field is weak, far from the star, and/or promptly radiate from a large emitting zone at limited optical depth, rather than create a long-lasting, optically-thick, trapped photon-pair plasma. This could explain how such a short-duration event could attain peak luminosity $L_{\text{peak}} \simeq 3 \times 10^{44} D_{11}^2$ erg s$^{-1}$ with a hard spectrum, comparable to the peak luminosity of a giant flare, at a distance $D = 11 D_{11}$ kpc (Corbel et al. 1999).

- Timing studies of AXP 1E2259+586 revealed a glitch associated with a burst-active episode in June 2002, plausibly simultaneous with the onset of bursting (Kaspi et al. 2003; Woods et al. 2003b). The star’s rotation rate abruptly increased by 4.2 parts in $10^6$, giving evidence for the redistribution of angular momentum between superfluid and non-superfluid components within the star. A sudden adjustment within the star is necessary, thus the bursting episode was probably not due to pure magnetospheric instabilities.∗

- No significant, persistent diminishment of $\dot{P}$ was detected in SGR 1900+14 following the 1998 August 27 giant flare (Woods et al. 1999). This puts constraints on large-scale rearrangements of the magnetosphere (Woods et al. 2001) in the context of the globally-twisted magnetosphere model (TLK). In this model, twists are maintained in the force-free magnetosphere by currents flowing along field lines. Such twists could be driven by a strong, “wound up” interior field, stressing the crust

∗ Note that the June 2002 glitch in AXP 2259+586 (Kaspi et al. 2003; Woods et al. 2003) was different from previous spin-down irregularities in this star during the past 25 years. I say this because the star has been spinning down at a steady rate during the $\sim 5$ years since phase-coherent timing began (Kaspi, Chakrabarty & Steinberger 1999; Gavriil & Kaspi 2002), and the persistent (post-recovery) $\dot{P}$ changed by only $\sim 2\%$ during the glitch/bursting episode. If one extrapolates with this $\dot{P}$ back through the sparsely-sampled period history of the star, beginning with Einstein Observatory observations in 1979, one finds that the star must have experienced two episodes of accelerated spin-down, or two spin-down glitches, both with $(\Delta P/P) \sim +2 \times 10^{-6}$. The first occurred around 1985, between Tenma and EXOSAT observations. The second occurred after ASCA but before RXTE, during 1993-1996. One could alternatively fit the data with spin-up glitches, like the June 2002 glitch, as suggested by Usov (1994) and Heyl & Hernquist (1999), but this fit requires that the persistent value of $\dot{P}$ was larger in the past by $\sim 25\%$. In either case, this star was behaving differently in the past.
from below, which is a likely relic of magnetar formation (DT92). As shown by TLK, global twists tend to shift field lines away from the star, enhancing the field strength at the light cylinder and hence the braking torque. If the August 27 flare involved a relief of large-scale twists via reconnection, analogous to the instabilities of Wolson (1995) and Lynden-Bell & Boiley (1994), with significant diminishment of global currents (a possibility raised by TLK and Lyutikov 2003), then one would expect a diminishment in $\dot{P}$. In fact, there was no significant change in $\dot{P}$ immediately after the flare, but $\dot{P}$ significantly increased over the years which followed (Woods et al. 2002; Woods 2003a; Woods 2003b). This gives evidence that the net effect of the 1998 magnetic activity episode, including the giant flare, was to increase the global twist angle and global currents, in a way which did not immediately affect the near-open field lines, far from the star (C. Thompson, private communication). A complete discussion of SGR torque variations will be given elsewhere. Here I simply want to point out that models of giant flares which posit that the whole magnetosphere is restructured, with largely dissipated currents, are not supported by SGR timing data.

This concludes my short list of new evidence. Thompson, Lyutikov & Kulkarni (2002; §5.6) gave three additional semi-empirical arguments for crustal shifts during the August 27 flare. They also gave one countervailing argument, based upon the softening of SGR 1900+14’s spectrum after the giant flare. But later work (Lyubarski, Eichler & Thompson 2002) suggested that the immediate post-burst emission was dominated by surface afterglow with a soft, thermal spectrum (which is presumably modified by scattering outside the star).

Lyutikov (2003) noted five pieces of evidence which favor magnetospheric instabilities. His first point was based on X-ray pulse-profile changes in SGR 1900+14. These same observations were invoked by TLK to argue the other way, so I think that this evidence is ambiguous. (See §5 in Woods et al. 2003a for a complete discussion.) Some of his other points might have alternative interpretations, as he himself notes. In particular, the mild statistical anti-correlation between burst fluence and hardness (Göğüş et al 2002) could be due to emission-physics effects, independent of trigger details, as suggested by Göğüş et al. Incidentally, this mild trend seems to go the other way in AXP bursts (Gavriil, Kaspi & Woods 2003).

### 1.5 Discussion: crust failure in magnetars

A magnetar’s crust is a degenerate, inhomogeneous Coulomb solid in a regime of high pressure, magnetization, and stress which has no direct experimental analog. It lies atop a magnetized liquid crystal which is subject to unbearable Maxwell stresses from the core below. Its behavior is thus quite uncertain. The crust cannot fracture like a brittle terrestrial solid, which develops a propagating crack with a microscopic void (Jones 2003), but it may experience other instabilities, such as “mock fractures” (§2 above).

The magnetar model was developed in a series of papers by Thompson and myself which invoked magnetically-driven crust fractures. Most of this work will remain valid if magnetar crusts prove to yield only plastically with no instabilities. However, some of the outburst physics would return closer to the original conception of DT92 and Paczyński (1992), along with several other changes.
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For example, TD96 considered “Hall fracturing” in the crusts of magnetars. This was a consequence of “Hall drift” (Jones 1988; Goldreich & Reisenegger 1992), whereby the Hall term in the induction equation drives helical wrinkles in the magnetic field, which stress the crust. In magnetars, but not in radio pulsars, the wrinkled field is strong enough to drive frequent, small-scale crust failure as ambipolar diffusion within the core forces flux across the crust from below. TD96 suggested that this crust failure occurs in small fractures which generate a quasi-steady flux of high-frequency Alfvén waves, energizing the magnetosphere and driving a diffuse wind out from the star. There seemed to exist direct evidence for this: a bright, compact radio nebula that was believed to surround SGR 1806-20 (Kulkarni et al. 1994; Sonobe et al. 1994; Vasisht et al. 1995; Frail et al. 1997). However, the high power of this nebula required rather implausibly optimized physical parameters and efficiencies, which caused concern.∗ Then Hurley et al. (1999b) found evidence that SGR 1806-20 is not precisely coincident with the central peak of the radio nebula. Chandra measurements verified that the SGR is displaced 14′′ from the radio core (Eikenberry et al. 2001; Kaplan et al. 2002). It now seems likely that many, or perhaps all, Hall-driven yields in a magnetar’s crust are plastic, occurring via dislocation glide in the outer crust (ρ < ρdrip) and microscopic shear-layers at depth. This probably dissipates magnetic energy locally as heat, rather than as Alfvén waves in a corona. Still the basic analysis of TD96 is valid with this reinterpretation.

I want to emphasize that crustquakes in magnetars cannot be ruled out.∗ Besides sudden yields of nuclear pasta and “mock fractures” involving fault-line liquification (§2), magnetic-mechanical instabilities in the outer layers of magnetars, where magnetic pressure is not insignificant compared to the material pressure, may be associated with the emergence of magnetic flux, as in solar activity (e.g., Solanski et

∗ Because the magnetar model predicted that SGR 1806-20 was rotating slowly (as later verified; Kouveliotou et al. 1998) this nebula could not have been rotation-powered. Fracture-driven Alfvén waves from an active, vibrating crust thus seemed necessary, beginning in October 1993 (when the radio nebula discovery was announced at the Huntsville GRB Workshop: Frai & Kulkarni 1994; Murakami et al. 1994) through most of the 1990’s. The probability for a chance overlap of the radio plerion core with the ∼ 1 arcmin ASCA X-ray box for the SGR (Murakami et al. 1994) was initially estimated in the range \( \lesssim 10^{-6} \). When a coincident, extremely reddened Luminous Blue Variable (LBV) star was discovered (Kulkarni et al. 1995; van Kerkwijk et al. 1995) smaller probabilities for chance coincidence were implied, so the LBV star was presumed to be a binary companion to the plerion-powering neutron star. It turns out that the LBV star may be the brightest star in the Galaxy, with luminosity \( L > 5 \times 10^6 L_\odot \) (Eikenberry et al. 2002; Eikenberry et al. 2003), thus it probably can power the radio nebula by itself (e.g., Gaensler et al. 2001; Corbel & Eikenberry 2003). The chance for this \( M > 200 M_\odot \) star to lie within 14′′ of another nearly-unique galactic star, SGR 1806-20, is fantastically small. This seems to be a lesson in the dangers of a posteriori statistics, or the treachery of Nature, or both.

∗ There is evidence for quite localized crust shifts during some magnetar outbursts. The radiative area of the thermal afterglow of the 1998 August 29 event was only \( \sim 1 \) percent of the neutron star area (Ibrahim et al. 2001) consistent with an “aftershock” adjustment along a fault zone that was active in the August 27 flare. A similarly small radiative area was found following the 2001 April 28 burst which seemed to be an aftershock of the April 18 flare (Lenters et al. 2003; Feroci et al. 2003). Observations of AXP 1E2259+586 during its June 2002 activity (Woods et al. 2003) showed an initial, hard-spectrum, declining X-ray transient with a very small emitting area during the first day following the glitch, while the emitting area of the slowly-declining thermal afterglow observed over the ensuing year was a sizable fraction of the star’s surface. This suggests that there was a small region of the crust where the magnetic field was strongly sheared, perhaps along a fault; and a large area in which it experienced more distributed plastic failure.
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al. 2003). Wherever crustal fields exceed $\sim 10^{16}$ Gauss, intrinsic magnetization instabilities may be possible (Kondratyev 2002). Finally, rapid stress-changes exerted on the crust by the evolving core field from below, or by a flaring corona from above, could drive catastrophic failure.

1.6 Conclusions

In conclusion, a magnetar is a sun with a crust. Both crustal and coronal instabilities are possible, as well as instabilities within the core, which is coupled to the crust from below by the diffusing magnetic field. Physical conditions are much more complicated than those which prevail on either the Earth or the Sun, and the available data is much more fragmentary, so the challenge of understanding these stars is great.

In this review, I have described evidence that rapid interior stellar adjustments occur during some magnetar outbursts and bursting episodes. Based on this evidence, it seems likely that plastic crust failure initiates bursting episodes in SGRs and AXPs, by triggering a sequence of reconnection instabilities in the magnetosphere which are observed as “ordinary” common SGR (and AXP) bursts. Ongoing, relatively rapid plastic motion of patches of crust during these burst-active episodes (compared to what occurs in the quiescent state) could explain why bursts come in “swarms” with the time between bursts much longer than the durations of the bursts themselves.

The “relaxation system” behavior found by Palmer (1999) may be due to the (quasi)steady loading of magnetic free energy within the magnetosphere by the plastic motion of magnetic footpoints. Palmer’s “energy reservoir” would then be the sheared or twisted (i.e., non-potential) components of the exterior magnetic field, steadily driven by plastic motion of the magnetic footpoints during active periods, and undergoing sporadic, catastrophic dissipation in bursts of reconnection.* If the reservoir is an arch of field lines with one footpoint anchored on a circular cap of radius $a$ that is slowly twisting at rate $\dot{\phi}$, then the loading rate is $\dot{E} \sim (1/4)a^3 B^2 \dot{\phi}$, independent of the length of the arch in a first, crude estimate. For a cap diameter $\sim 1$ km, comparable to the crust depth, this implies $\dot{\phi} \sim 0.06 (B_{14}/3)^{-2} (a/0.5 \text{ km})^{-3}$ radians/day during Palmer’s interval B, and 25 times slower during Palmer’s interval A. The durations of these burst-active intervals would then be time-scales for significant local crust-adjustments, exceeding by $\gtrsim 10^6$ the time-scales for reconnection within individual bursts.

There is little doubt that profound exterior reconnection occurs in magnetar flares (TD95). There are two triggering possibilities:

(1) A catastrophic, twisting crust-failure might occur during the flare, so that significant (magnetic) energy from within the star contributes to the flare emissions. If the solid crust yields plastically, then this would require a sudden stress-change applied upon the solid from below; but crustal instabilities cannot be ruled out (§5).

(2) Flares might develop in the magnetosphere, with little energy communicated from below on the time-scale of the flare. This could be a spontaneous instability reached via incremental motion of the magnetic footpoints; but ongoing plastic failure of the crust seems more likely as a trigger.

* This differs from previous suggested explanations of the Palmer Effect, which involved energy reservoirs within the crust.
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Clearly, these are not fully-distinct possibilities. Let us set the dividing line at \( \sim 0.1 \) of the energy coming from within. Then, at present, I favor mechanism (1) for the 1998 June 18 flare from SGR 1627-41; and mechanism (2) for the 1998 August 27 flare from SGR 1900+14.

The back-reaction of an exterior magnetic stress-change on the crust could drive shallow crust failure and heating that is consistent with the August 27 flare afterglow (Lyubarsky, Eichler & Thompson 2002). But this back-reaction could not account for the 1998 June 18 afterglow if interpreted as deep crust-heating (Kouveliotou et al. 2003). The slow-peaking, tail-free June 18 event (Mazets et al. 1999b) plausibly involved a deep crust and/or core adjustment in a star with a relatively quiet, relaxed magnetosphere, far from the critical state, so that little exterior reconnection was induced (relative to the giant flares).

Note that even the August 27 event was probably not a spontaneous, pure magnetospheric instability. A soft-spectrum precursor-event detected 0.45 s before the onset of the 1998 August 27 event (Hurley et al. 1999a; Mazets et al. 1999a) suggests that the crust was experiencing an episode of accelerated plastic failure. Plastic creep probably continued during the first \( \sim 40 \) seconds after the flare’s hard spike, giving rise to the “smooth tail” part of the light curve (Feroci et al. 2001; §7 in TD01). Subsequent spindown measurements (§4) suggest that large-scale currents in the magnetosphere were enhanced rather than dissipated during the magnetically-active, flaring episode.

Of course, much more work is needed to develop and test these hypotheses. Many mysteries persist, but it seems that the magnetar model has the physical richness needed to accommodate diverse observations of SGRs and AXPs. The path to full scientific understanding of these objects will no doubt be long and interesting.

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