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Soft Gamma Repeaters: New Results and Surprises from Swift, INTEGRAL, and the Interplanetary Network

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Abstract The history and observational properties of the soft gamma repeaters are reviewed. Over the past decades, we have gone from viewing these objects as a special class of cosmic gamma-ray burst, to seeing them as one manifestation of magnetars. There is now a solid body of multi-wavelength observations, as well as some more controversial properties. There are indications that extragalactic giant magnetar flares have been detected. There are still a number of fundamental unanswered questions, which will require better theory, more sensitive observations, and many years to answer.

Key words: neutron stars — magnetars

1 INTRODUCTION

The story of the soft gamma repeaters (SGRs) begins in 1979. On January 7th, a short duration, soft spectrum burst was observed from the direction of the Galactic center (Laros et al. 1986). At that time, relatively little was known about cosmic gamma-ray bursts (GRBs), but their energy spectra, as observed up to that point, were clearly hard. On the other hand, it was clear that the spectrum of the January 7 event was much softer than that of a GRB, and it was called "a gamma-ray burst without the gamma-rays". (Today we would call it a short SGR burst.) Several months later, the most intense gamma-ray transient which had been observed up to that time, the March 5 1979 burst, was detected. This event had a hard spectrum and a long duration, with a pulsating tail, and it was localized to the N49 supernova remnant in the Large Magellanic Cloud (Cline et al. 1980; Evans et al. 1980). At the distance of the LMC, the intensity of this burst was $> 10^3$ times the Eddington luminosity. (Today we would call this a giant magnetar flare.) In the days that followed, smaller bursts were detected from the source (Mazets et al. 1979a). Many theories were proposed to explain this event, which was generally thought to be an unusual GRB. Several weeks later, another repeating source was discovered when it emitted three short duration, soft spectrum bursts in three days (Mazets et al. 1979b). Finally, between July and December 1987, yet another repeater was discovered (Atteia et al. 1987). This object turned out to be the same as the one which had been detected on January 7, 1979. The source was named SGR 1806–20, with SGR standing both for the constellation (Sagittarius) and for Soft Gamma Repeater, to distinguish it from the GRBs.

On the theoretical side, two papers appeared independently in 1992 which considered the role of strong magnetic fields in explaining GRBs in general, and the March 5 1979 event in particular (Duncan & Thompson 1992; Paczyński 1992). These papers lay the groundwork for the 1995 paper which explained the SGRs as strongly magnetized neutron stars (Thompson & Duncan 1995). The word "magnetar" was used in it to describe these neutron stars for the first time. In these papers, one can find many roles that the magnetic field plays in explaining the SGR phenomenon, but two important ones are the following:

– It provides a robust magnetosphere that confines the hot e^-e^+ pair plasma required to produce the intense peak of the March 5 1979 burst.

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– It suppresses the Compton scattering of outgoing radiation from the neutron star so that it can greatly exceed the Eddington limit, without invoking beaming.

The definition of a magnetar is a neutron star in which the magnetic field, rather than rotation, provides the main source of free energy; the decaying field powers the electromagnetic radiation (Duncan & Thompson 1992; Thompson & Duncan 1995, 1996). Note that the definition does not specify any particular field strength, but rather, is based on an energy balance argument. Today we know of several possible manifestations of magnetars, and soft gamma repeaters are one. With inferred magnetic field strengths $B \sim 10^{15}$ G, magnetars indeed have the strongest cosmic magnetic fields that we know of in the Universe. But we also know of neutron stars with strong magnetic fields that are rotation-powered, and clearly do not fit the magnetar description (e.g. McLaughlin et al. 2003).

2 THE BASIC FACTS

Although there are still many things that are not well understood about magnetars, there are a few basic, observational facts that are not controversial, and require little or no interpretation.

– The SGRs are sources of short ($\sim$ 100 ms), repeating bursts of soft γ-radiation ($<$100 keV). Figure 1 shows a series of bursts from SGR 1900+14. When an SGR is active, it can go through periods where hundreds of bursts are emitted in a period of minutes. Active periods occur at apparently random intervals; outside of these periods, it is common for SGRs to emit no detectable bursts at all for years.

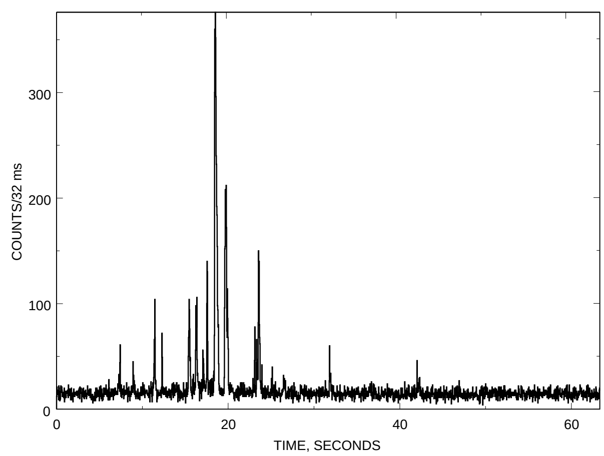

Fig. 1 Bursts from SGR 1900+14 during a particularly active phase. The data are from the Ulysses GRB experiment, for May 30, 1998, in the 25–150 keV energy range. Active phases occur apparently at random, and no bursts are observed during quiescent phases, which can last for years.

– Four SGRs are known. Three are in our galaxy (SGR 1806–20, 1900+14, 1627–41), and one is in the direction of the Large Magellanic Cloud (SGR 0525–66, the source of the March 5, 1979 burst). Their general locations are shown in Figure 2. The fact that three are in the Galactic plane, while one is in a young SNR, indicates that all the SGRs are probably young objects (perhaps $<$10 000 years old).
– The SGRs are quiescent X-ray sources and have been imaged by most X-ray spacecraft since ROSAT. Although their luminosities are somewhat variable, they are generally strong sources ($\sim 10^{-11}$ erg cm^{-2} s^{-1}) which can easily be detected in soft X-rays, and in two cases, to energies up to 100 keV and above (Götz et al. 2006a,b). While there is a connection between the X-ray luminosity and bursting activity, the quiescent X-ray emission is always present, even when there are no bursts.

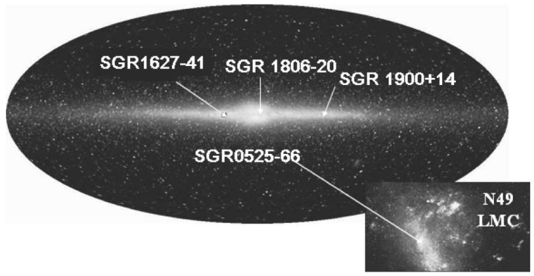

Fig. 2 The general locations of the four known soft gamma repeaters.

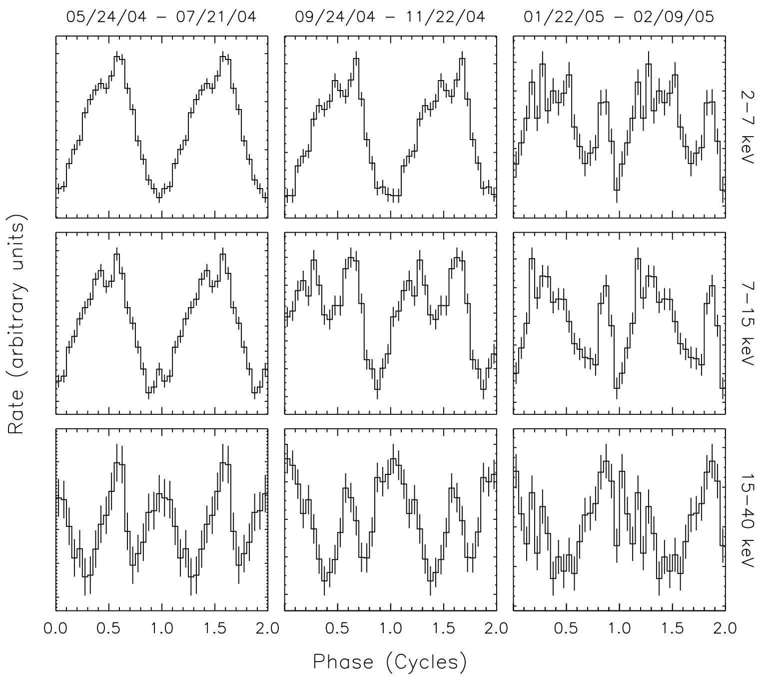

Fig. 3 X-ray pulse profiles of SGR 1806–20 as a function of energy, and of time before and after the giant flare of December 27 2004, from Woods et al. (2007). Reproduced by permission of the AAS.

– The SGRs have rotation periods in the 5–8 s range, which are increasing monotonically, although sometimes irregularly, with time, at rates $\sim 10^{-10}$ s s^{-1}. Figure 3 shows the X-ray pulse shape of SGR 1806–20. The X-ray luminosity ($\sim 2\times10^{35}$ erg s^{-1}) is much greater than the spin-down energy ($\sim 10^{33}$ erg s^{-1}), which leads to an estimate of the magnetic field if dipole radiation is assumed to be the cause of the spindown, and the particle wind is negligible (Kouveliotou et al. 1998). Also, under these conditions, the spindown age $P/2\dot{P} \sim 1500$ yr, which is consistent with the idea that SGRs are young objects. SGR 1627–41 may be an exception. Its periodicity is either undetectable, or its amplitude is time-variable (Woods et al. 1999; Hurley et al. 2000).
– The SGRs occasionally emit long duration, hard spectrum *giant flares* , which produce the most intense cosmic gamma-ray fluxes ever measured at Earth. Three have been observed so far. The first was the March 5, 1979 event from SGR 0525–66 (Mazets et al. 1979a; Cline et al. 1980; Evans et al. 1980).

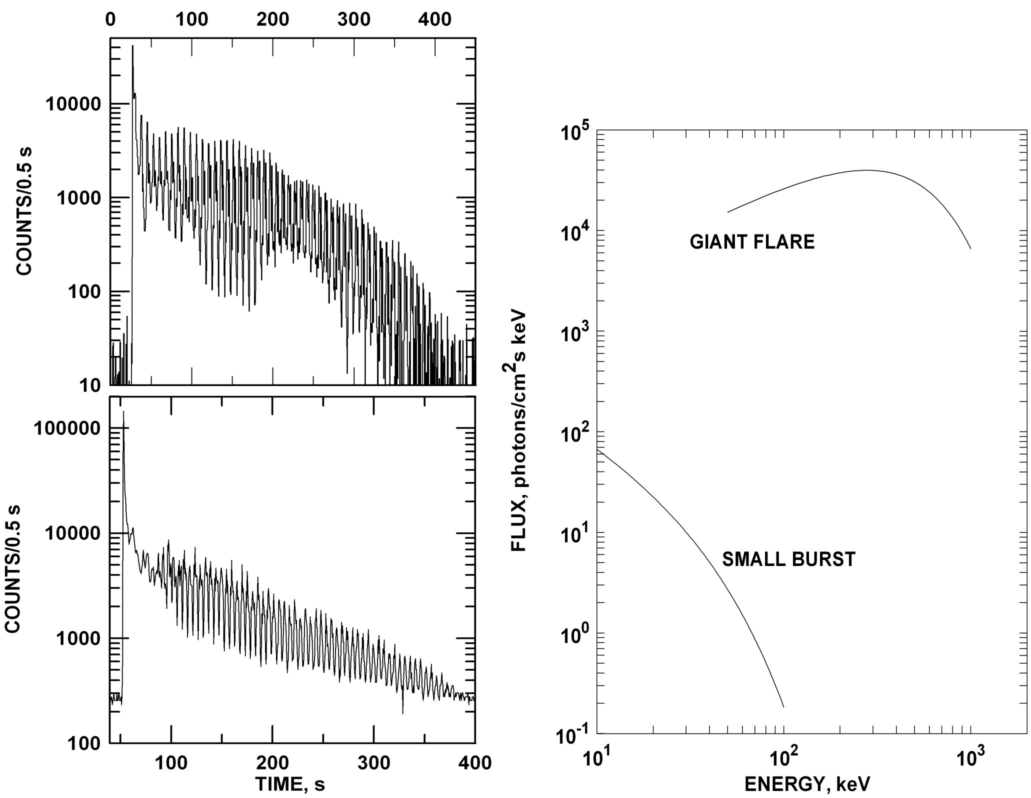

Fig. 4 Left: time histories of the giant flares from SGR 1900+14 (bottom, Ulysses data) and SGR 1806–20 (top, RHESSI data). The common features of giant flare time histories are 1) a fast rise ($<$ 1 ms) to maximum, 2) a $\sim$ 200 ms long intense peak, and 3) a several hundred second long tail which is modulated by the neutron star rotation period. Right: comparison of the typical energy spectra of a short SGR burst and a giant flare. The giant flare is not only more intense, but has a considerably harder energy spectrum during the intense peak. Emission up to $\sim$17 MeV has been observed.

The second was the August 27, 1998 event from SGR 1900+14 (Hurley et al. 1999; Feroci et al. 1999; Mazets et al. 1999). The third was the December 27, 2004 burst from SGR 1806–20, the most intense of the three (Hurley et al. 2005; Mereghetti et al. 2005; Palmer et al. 2005). Giant flares occur perhaps every 30 years on a given SGR (no SGR has yet been observed to emit two giant flares, so this number is based on the number of known SGRs, the number of years of more or less complete observations, and the three observed giant flares). These bursts are intense (up to $\sim 3 \times 10^{46}$ erg at the source, or 1 erg cm^{-2} at Earth), last $\sim$ 5 minutes, and have very hard energy spectra extending to MeV energies, at least. Their time histories are modulated with the neutron star periodicity. SGRs are not quiescent radio emitters (Lorimer & Xilouris 2000), but giant flares create transient radio nebulae (Frail et al. 1999; Gaensler et al. 2005), and even produce dramatic ionospheric disturbances (Inan et al. 1999). Figure 4 shows two examples, and compares the spectrum of a giant flare with that of a short burst.

3 THE LESS CERTAIN FACTS

There are a number of SGR properties whose interpretation is more complex, or less certain. The first involves burst statistics. The distributions of the short burst durations (Fig. 5) and the waiting time between two successive bursts have been studied by Göğüş et al. (2001), who have shown that both are lognormal. A cumulative number-intensity distribution has been compiled recently using INTEGRAL-IBIS observations by Götz (2006a), who has found that it follows a power law (Fig. 6).

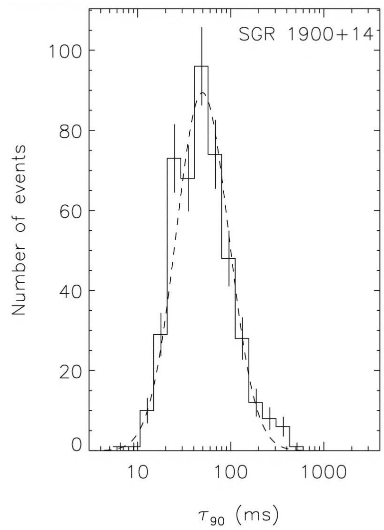

Fig. 5 Distribution of the durations of the short bursts from SGR 1900+14 (solid line), and a lognormal fit (dashed line, from Göğüş et al. 2001). The bursts were observed by BATSE. Reproduced by permission of the AAS.

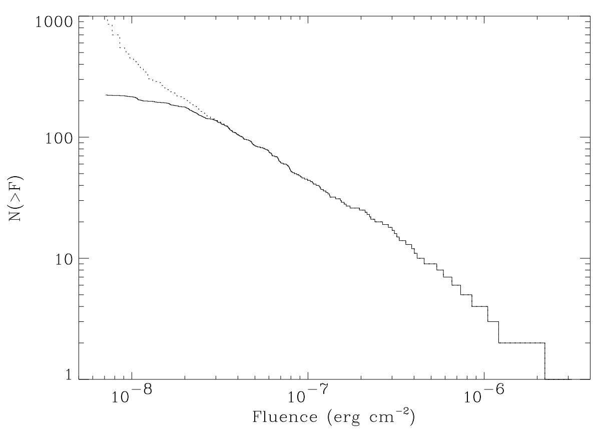

Fig. 6 The number-intensity relation for short duration bursts from SGR 1806–20, from Götz et al. (2006a). The bursts were observed by INTEGRAL-IBIS. The solid line represents the raw data; the dashed line is the result after correcting for efficiency.

Göğüş et al. (2001) have argued that lognormal duration and waiting time distributions, and the power law number-intensity distribution, are consistent with a system in a state of self-organized criticality, i.e., a system which evolves to a critical state due to some driving force. In this state, a slight perturbation can cause a chain reaction of almost any size. Here, the system is the neutron star crust, and it evolves to a critical state due to the force exerted by magnetic stress. The chain reaction is a crustquake, and it leads to a short burst of arbitrary size (but not a giant flare). Palmer (1999) has shown that this behavior is also consistent with a set of independent relaxation systems. In this picture, multiple, independent sites on the neutron star surface accumulate energy, and that energy is suddenly released seismically, producing short bursts.

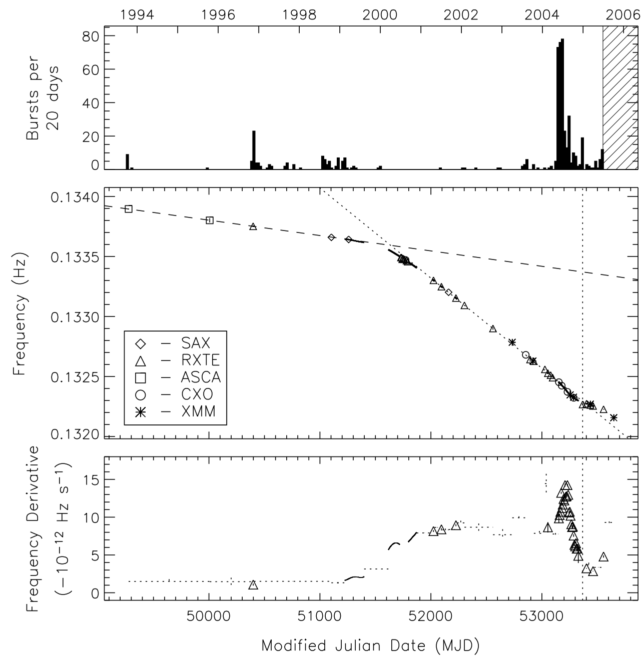

Fig. 7 From Woods et al. (2007). Top panel: bursting activity of SGR 1806–20 in 2004 and 2005. Middle panel: spin frequency as a function of time over the same period. The giant flare occurred at the end of 2004. Bottom panel: frequency derivative. Reproduced by permission of the AAS.

The second involves line features. The RXTE PCA spectra of ~ 6 bursts from SGR 1806–20 show evidence for one or more lines (at $\sim$ 5, 11, and 17 keV), which can be interpreted as cyclotron features (Ibrahim et al. 2002, 2003). If these are assumed to be electron cyclotron features, a field strength $\mathrm{B} \sim 6 \times 10^{11}$ G is inferred, but much greater line widths are expected due to thermal broadening. If proton cyclotron features are assumed instead, $\mathrm{B} \sim 8 \times 10^{14}$ G is obtained, which is consistent with magnetar- strength fields. If confirmed, these observations would constitute the first direct measurement of the field strength of a magnetar. A 6.4 keV emission line has been observed in the spectrum of a burst from SGR 1900+14, with a possible weaker line at 13 keV. The interpretation could be Fe fluorescence from material ablated from the neutron star surface, or again, cyclotron features (Strohmayer & Ibrahim 2000). Lines in the spectra of transient events, such as SGR bursts, are difficult to verify, so the interpretation of these observations remains open. Line features have not been detected in the quiescent X-ray spectra of SGRs (Molkov et al. 2005).

The third is the relation between bursting and other activity. Woods et al. (2002, 2007) have shown that the spindown, while monotonic, is variable, and that the variability is not always related to bursting activity (Fig. 7); for SGR 1806–20 this includes both the short duration events and the giant flare. This is an argument against accretion as the cause of the bursts. On the other hand, bursting activity and the intensity of the quiescent emission are related (Fig. 8). The relation between the two is probably a complex one, but a simple explanation is that both are related to magnetic stressing of the neutron star surface.

The fourth is the interpretation of the IR flux from SGR 1806–20. In 2005, two groups succeeded in detecting the faint IR counterpart to this SGR in a very crowded field (Israel et al. 2005; Kosugi et al. 2005). The identification was based in large part on the IR variability, which was roughly correlated in time with the bursting activity and the quiescent flux increase in 2004. However, Israel et al. (2005) have pointed out

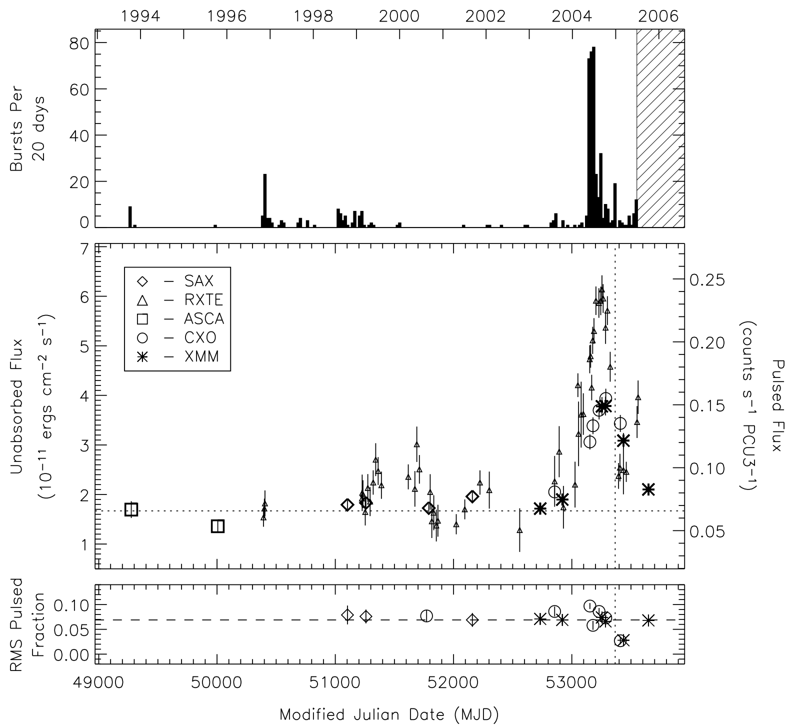

Fig. 8 From Woods et al. (2007). Top panel: bursting activity of SGR 1806–20 between 1993 and 2005. Middle panel: low energy X-ray flux, as measured by various spacecraft. The quiescent flux increases at the same time as the bursting activity in 2004. Bottom panel: pulsed fraction. Reproduced by permission of the AAS.

that the IR flux is many orders of magnitude above the extrapolation of the X-ray spectrum. Thus the two probably have different origins, even though they seem to vary in concert.

The fifth is the nature of three mystery objects, which may or may not be SGRs. SGR 1801–23 was discovered by the interplanetary network when it emitted two short duration, soft spectrum bursts (Cline et al. 2000). SGR 1808–20 was discovered by the HETE spacecraft when it emitted one short duration, soft spectrum event (Lamb et al. 2003). GRB 050925 was discovered by Swift; it too, has emitted just one short, soft event (Holland et al. 2005; Markwardt et al. 2005). (One should recall that SGR 1806–20 was discovered when it emitted a single burst on January 7 1979, so the lack of observed repetition to date for two of these objects is not a strong argument against an SGR origin.) All these objects lie in the Galactic plane, which is another argument in favor of an SGR interpretation. However, no quiescent X-ray source has been found for any of them, which would be unusual for an SGR.

The sixth is the relation of SGRs to supernova remnants (SNRs) and massive star clusters. While some SGRs appear to lie in or near SNRs, it can be argued that this is not unlikely based on chance superpositions (Gaensler et al. 2001). Other SGRs appear to lie in massive star clusters (Eikenberry et al. 2004), although the probability of chance alignments is harder to judge. In any case, the distances to the Galactic SGRs are generally uncertain by a factor of at least two.

4 INTERPRETATION

Several interpretations of SGR phenomenology have been proposed. Here the magnetar model will be outlined, as it has been elaborated by Thompson and Duncan (1995, 1996) and reviewed by Woods and Thompson (2006).

In some rare supernova explosions, a neutron star is born with a fast rotation period ($\sim$ ms) and a dynamo is established which creates or amplifies a strong magnetic field. Differential rotation and magnetic braking quickly slow the period down to the observed 5–10 s range. Magnetic diffusion and dissipation heat the neutron star surface, which radiates X-rays. This X-radiation is always present, regardless of the bursting activity, so magnetars are quiescent X-ray sources. In addition, increased dissipation at the poles creates hot spots on the surface, and a periodic component whose amplitude is $\sim 10\%$ of the total is superimposed. Thus magnetars are quiescent, periodic X-ray sources. The strong magnetic field ($\sim 10^{15}$G) stresses the iron surface of the neutron star, to which it is anchored. The surface, a crustal lattice with a finite shear modulus, undergoes localized cracking, shaking the field lines and injecting energy into the magnetosphere. The resulting Alfvèn waves accelerate electrons to $\sim$ 100 keV; they radiate their energy in short bursts with energies around $10^{40} - 10^{41}$ erg (in earthquake terms, this can be thought of as a magnitude 19.5 crustquake). These are the most common SGR bursts.

Localized cracking cannot relieve all the stress which the magnetic field exerts on the surface, and it continues to build for decades. The built-up stress eventually ruptures the surface of the star profoundly (a magnitude 23.2 starquake), resulting in a giant flare. Magnetic field lines annihilate, accelerating electrons and positrons, and filling the magnetosphere with a hot pair plasma. The initial spike in the giant flare is radiation from the entire magnetosphere ($\mathrm{B} > 10^{14}$ G is required to contain the pair plasma). The 5 minute long, periodic component of the flare comes from hot spots on the surface of the neutron star.

5 MAGNETAR MANIFESTATIONS

To date, we know of 4 definite SGRs, and 3 possible ones. The anomalous X-ray pulsars (AXPs, the subject of other papers in this volume) are also interpreted as magnetars, and about 8 of them have been identified, all in the Galaxy. Table 1 compares some of the essential properties of SGRs and AXPs. (For a recent review of SGR and AXP properties see Woods and Thompson 2006).

Table 1 AXPs and SGRs Compared

	SGRs	AXPs
Short duration bursts	Frequent	Rare, weaker
Giant flares	Yes	None observed
Quiescent X-ray emission	Yes	Yes
Radio emission	Following giant flares	1 case known
Periods	5.2 – 8 s	5.5 – 11.8 s
Spindown	$6.1 - 20 \times 10^{-11}\mathrm{s\,s^{-1}}$	$0.05 - 10 \times 10^{-11}\mathrm{s\,s^{-1}}$
Hosts	Massive star clusters, SNRs?	SNRs?

A third manifestations of SGRs might be some short duration cosmic gamma-ray bursts "in disguise" (that is, events which have been incorrectly classified as gamma-ray bursts). If an SGR giant flare were observed from a great distance, only the short duration, hard spectrum initial spike would be detectable. It would resemble a short duration GRB, and, based on the energetics of the giant flares observed so far, such a burst could be detected to a distance of perhaps 100 Mpc (Hurley et al. 2005). Evidence for an SGR origin would be a bright galaxy in the error box. Two such events have possibly been observed. The error box of GRB051103 includes part of M81 (Golenetskii et al. 2005), and the error box of GRB070201 includes part of M31 (Hurley et al. 2007, Figure 9). Both cases are plausible, but not proven beyond a doubt. Thus, although it seems virtually certain that extragalactic SGRs must exist, none has been detected with certainty (apart from SGR 0525–66 in the LMC). The percentage of short duration events which might be extragalactic giant magnetar flares is therefore uncertain, but estimates vary between 1 and 15% (Nakar et al. 2006, Ofek 2006).

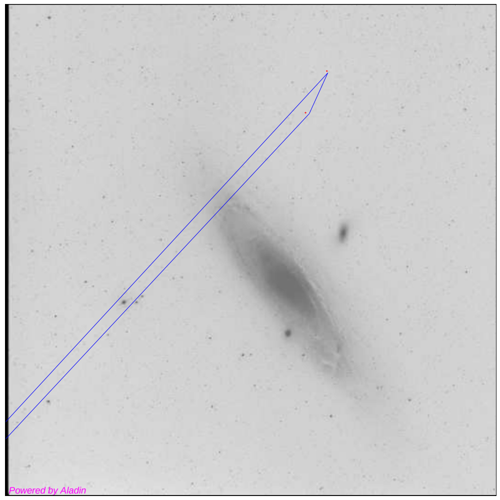

Fig. 9 The IPN error box of the short GRB070201 and M31. This figure was created in Aladin (Bonnarel et al. 2000).

6 OPEN QUESTIONS

Some of the outstanding questions about SGRs are the following.

1. What are the distances of the Galactic magnetars? The present uncertainty results in about an order of magnitude uncertainty in the energetics.
2. What is the number-intensity relation for giant magnetar flares?
3. What is the SGR birth rate? If this were known, we would be able to better constrain the total number of SGRs in our galaxy, and their lifetimes.
4. What kind of supernova produces an SGR? This may not matter much for understanding SGR activity, because it is probably independent of how the magnetar formed. But it is an essential open question in magnetar theory.
5. What is the relation between SGRs and AXPs? Does one evolve into the other, or are they separate manifestations of magnetars? A related question is what the relation is between magnetars and the high magnetic field pulsars.
6. How many other manifestations of magnetars are there waiting to be discovered?

The answers to these questions will come from three efforts. The first is more detailed theoretical modeling of magnetar formation and activity. The second is more sensitive detectors. Today the interplanetary network surveys the entire sky for magnetars, with a duty cycle close to 100%, but it only detects the more intense bursts. Swift and INTEGRAL-IBIS are extremely sensitive SGR detectors, but they view only a small fraction of the sky. Sensitivity should not be achieved by sacrificing field of view, because the entire sky needs to be surveyed for magnetar activity with greater sensitivity on a continuous basis. With these two elements in hand, one more thing will be required: about 30 years of data. This estimate comes from two facts. The first is that we have now been studying magnetars for about 30 years to arrive at our current state of knowledge. There are not many of them, and they are not active all the time. They yield their secrets very slowly. The second is that this is our best estimate of the time between giant bursts on a single SGR.

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DISCUSSION

D. FARGION: Three questions. Why didn't $P\dot{P}$ change during the December 2004 event? How can a neutron star undergo a precursor event to a giant flare, and 120 seconds later, explode again as another event? Why did $P\dot{P}$ change in October 2004 by a factor of 7? Who paid the bill?

K. HURLEY: Presumably, $P\dot{P}$ didn't change much during the giant flare because the energy did not come from material accreted onto the neutron star, but rather, it was seismic energy. As for the precursor emission, this is often interpreted as "the last straw that broke the camel's back"; that is, it was a large crustquake. As for the $P\dot{P}$ change in October 2004, this was presumably caused by torques exerted by the magnetic field.

G. S. BISNOVATYI-KOGAN: Giant SGR flares should be observed as short GRBs from other galaxies, as you said. There should therefore be rather strong short bursts from local group galaxies, and even the Virgo cluster. Is the absence of such events statistically consistent with present estimates of giant flare energies?

K. HURLEY: Actually, I think that there must be examples, say in the BATSE data, of short bursts which *are* giant magnetar flares. The problem is that the error boxes are too large to draw any definite conclusions about the host galaxies.

E. PIAN's comment and question: I would like to add something to the three possible magnetar manifestations that you discussed (SGR's, AXP's, short GRB's), namely the hypothesis that XRF's, or at least a fraction of them, are magnetars. In Mazzali et al.'s 2006 Nature paper we proposed that the magnetar forms as the remnant of the supernova explosion associated with the XRF. This magnetar may make short GRB's in the future.
Is there any afterglow emission from GRB 051103 or 070201 that could help you elaborate on the magnetar hypothesis?

K. HURLEY: I agree with your comment. The answer to your question is no, there was no detectable afterglow emission. Since this is so much weaker than the peak of the giant magnetar flares, we would not expect to detect it in these observations.

N. REA: The lines detected by Ibrahim et al. in SGR 1806–20 were disputed by Göğüş and Woods. Do you have any other news about this?

K. HURLEY:I know that as recently as last year, at the Isolated Neutron Star meeting in London, Alaa Ibrahim presented these results again. But as I mentioned, they are controversial.

S. COVINO: For a few well studied short GRBs, together with the initial hard spike there is also a long-lasting soft emission. This emission is not pulsed. Do you know if there could be a mechanism to have soft unpulsed emission after a giant magnetar flare?

K. HURLEY: I can't think of one. There are two possibilities, however. One is that these bursts are not extragalactic magnetar flares, but rather, merger events. The second is that, since we have only observed three giant magnetar flares, we perhaps should not conclude that all their time histories are similar. I prefer the first explanation, however.