The 4.5 ±0.5 Soft Gamma Repeaters in Review

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Abstract. Four Soft Gamma Repeaters (SGRs) have now been identified with certainty, and a fifth has possibly been detected. I will review their X-ray and gamma-ray properties in both outburst and quiescence. The magnetar model accounts fairly well for the observations of SGR1806-20 and SGR1900+14, but data are still lacking for SGR1627-41 and SGR0525-66. The locations of the SGRs with respect to their supernova remnants suggest that they are high velocity objects.

I INTRODUCTION

The Soft Gamma Repeaters are sources of short, soft-spectrum (≤ 100 keV) bursts with super-Eddington luminosities. They undergo sporadic, unpredictable periods of activity, sometimes quite intense, which last for days to months, often followed by long periods (up to years or decades) during which no bursts are emitted. Very rarely, perhaps every 20 years, they emit long duration giant flares which are thousands of times more energetic than the bursts, with hard spectra (≈ MeV). The SGRs are quiescent, and in some cases periodic, 1-10 keV soft X-ray sources as well. They all appear to be associated with supernova remnants, and a good working hypothesis is that they are all magnetars, i.e. highly magnetized neutron stars for which the magnetic field energy dominates all other sources, including rotation [6,29]. Figure 1 shows the time histories of bursts from SGR1900+14, and figure 2 shows a typical energy spectrum.

In this paper, I will mainly review the radio, X-ray, and gamma-ray properties of the SGRs in outburst and in quiescence, and indicate how the magnetar model accounts for these properties.

II SGR1806-20

Kulkarni and Frail [22] suggested that this SGR was associated with the Galactic supernova remnant (SNR) G10.0-0.3, based on its localization to a ≈ 400 arcmin.²
error box by the old interplanetary network (IPN) [1]. This was confirmed when ASCA observed and imaged the source in outburst, localizing it to a 1’ error circle [25]. A quiescent soft X-ray source was also detected by Cooke [5] using the ROSAT HRI. Based on more recent observations, Kouveliotou et al. [20] have found that the quiescent source is periodic (P=7.48 s) and is spinning down rapidly (Ṗ=2.8×10^{-11}s/s). If this spindown is interpreted as being due entirely to magnetic dipole radiation, the implied field strength is B=8×10^{14}G. The 2-10 keV X-ray luminosity of the source is 2×10^{35}erg/s, and the low energy X-ray spectrum may be fit by a power law with index 2.2.

The SNR G10.0-0.3 has a non-thermal core, and Frail et al. [8] have detected changes in the radio contours of the core on ∼year timescales. Van Kerkwijk et al. [30] have found an unusual star at the center of this core, which they identify as a luminous blue variable (LBV). The presence of this object has been a mystery up to now, because it was thought that the SGRs were single neutron stars. Recent work from the 3rd IPN has shed some light on this issue [13]. Figure 3 shows the location of the SGR superimposed on the radio contours of the SNR. It can be seen that the SGR is in fact offset from the LBV. The LBV may be powering the non-thermal core of the SNR, and causing the changes in the radio contours. It is also possible that the SGR progenitor was once bound to the LBV, but that it became unbound when it exploded as a supernova. A transverse velocity of ∼100 km/s would then be
required to explain the displacement between the two. Alternatively, it is possible that the apparent SGR-SNR association is due to a chance alignment of these two objects along the line of sight.

### III SGR1900+14

SGR1900+14 was discovered by Mazets et al. [23] when it burst 3 times in two days. A precise localization by the IPN [12] showed that this source lay just outside the Galactic SNR G42.8+0.6, with an implied proper motion >1000 km/s. The SGR is associated with a quiescent soft X-ray source [32,14,21]. The quiescent source has a period 5.16 s, and a period derivative $6.1 \times 10^{-11}$ s/s; again, assuming purely dipole radiation, $B \sim 8 \times 10^{14}$ G. The 2-10 keV luminosity is $3 \times 10^{34}$ erg/s, and the spectrum may be fit with a power law of index 2.2.

On 1998 August 27, the SGR emitted a giant flare which was probably the most intense burst ever detected at Earth [15]. Its luminosity was $2 \times 10^{43}$ erg/s in >25 keV X-rays, or $10^5 L_E$ (the Eddington luminosity). The time history of this burst clearly displayed the 5.16 s periodicity of the quiescent source (figure 4). The magnetic field strength required to contain the electrons responsible for the X-ray emission is > $10^{14}$ G; this constitutes an independent argument for the presence of strong fields in SGRs. From measurements of the ionospheric disturbance which this burst caused, Inan et al. [18] have estimated that there must have been one order
FIGURE 3. From Hurley et al. (1999b). Eight IPN annuli (lines), and the 1, 2, and 3 \( \sigma \) equivalent confidence contours (ellipses) for SGR1806-20. The best fit position and the position of the non-thermal core are indicated. The ASCA error circle is just visible in the lower left and upper left hand corners (Murakami et al. 1994). The ROSAT PSPC error circle is at the center; its radius is 11" (Cooke 1993). The 3.6 cm radio contours of G10.0-0.3 are also shown, from Vasisht et al. (1995).

of magnitude more energy in 3-10 keV X-rays than in >25 keV X-rays, bringing the total energy to \( \sim 4 \times 10^{44} \) erg. Frail et al. [9] detected a transient radio source with the VLA at the SGR position following the giant flare. This is the only case where a radio point source is present at an SGR position.

IV SGR0525-66

This SGR was discovered when it emitted the giant flare of 1979 March 5 [3,10]. It was localized by the IPN to a 0.1 arcmin\(^2\) error box within the N49 supernova remnant [7]. For an LMC distance of 55 kpc, this burst had a luminosity of \( 5 \times 10^{44} \) erg/s in X-rays >50 keV, or \( 2 \times 10^{6} \) \( L_E \); the total energy emitted was \( \sim 7 \times 10^{44} \) erg in >50 keV X-rays. The time history displayed a clear 8 s periodicity [2]. Both Duncan and Thompson [6] and Paczynski [26] suggested a strongly magnetized neutron star
as the origin of this burst. Although the source remained active through 1983 [11], it has not been observed to burst since then.

Rothschild et al. [27] found a quiescent soft X-ray point source in the SGR error box with a ROSAT HRI observation. As no energy spectra are obtained from the HRI, the soft X-ray luminosity can only be estimated by assuming various spectral shapes. The 0.1-2.4 keV luminosity is in the range $10^{36} - 10^{37}$ erg/s, depending on the assumed spectrum. No periodicity was detected in this observation, but the upper limit to the pulsed fraction is only 66%. If the age of the N49 SNR is taken to be 5 kyr [31], the implied transverse velocity of the SGR is several thousand km/s. *Chandra* observations of the SNR are scheduled, and are bound to reveal more about this interesting object.

V SGR1627-41

SGR1627-41 burst about 100 times in June-July 1998, and has not been observed to burst since then. During that period, observations by BATSE [34], *Ulysses* [16], KONUS-Wind [24], and RXTE [28] led to a precise source localization. The SGR lies near the SNR G337.0-0.1, at a distance of $\sim 11$ kpc. The implied transverse velocity of the SGR is in the range 200 - 2000 km/s. Although no giant flare has been observed from this source, there is a KONUS-Wind observation of an extremely energetic event [24]. The luminosity and total energy of the burst in the >15 keV range were $\sim 8 \times 10^{43}$ erg/s and $\sim 3 \times 10^{42}$ erg/s, respectively.

Like the other SGRs, this one also appears to be a quiescent soft X-ray source. *BeppoSAX* observations revealed a variable source with spectral index 2.1 and luminosity $\sim 10^{35}$ erg/s [35]. Although the *BeppoSAX* observations gave weak evidence...
for a possible 6.4 s periodicity, this was not confirmed in later ASCA observations of the source with better statistics [17].

VI SGR1801-23

The latest SGR to be discovered is 1801-23 [4]. It was observed to burst just twice, on June 29, 1997, by Ulysses, BATSE, and KONUS-Wind. The burst spectra were soft, and could be fit by an optically thin thermal bremsstrahlung function with a kT of $\sim 25$ keV. The time histories were short. In both respects, then, the source properties resemble those of the other SGRs. However, because only two bursts were observed, and they occurred on the same day, the IPN localization is not very precise. The error box is $3.8^\circ$ long, and has an area of $\sim 80$ arcmin$^2$. The source lies in the general direction of the Galactic center, and the error box crosses numerous possible counterparts (figure 5). The source would have a super-
Eddington luminosity for any distance > 250 pc; at the approximate distance of the Galactic center, its luminosity would be 1200L_E. At present, the best hypothesis is that this source is indeed an SGR; recall that SGR1900+14 was similarly detected when it burst 3 times in two days, and it remained quiescent for many years. Like SGR1900+14, the identification of SGR1801-23 may have to await a new period of bursting activity.

Table 1 summarizes the essential properties of the SGRs.

| SGR    | Super-Eddington Bursts? | Giant Flare? | Periodicity Observed in Burst? | Quiescent Soft X-ray Source? | Periodicity in Quiescent Source? | ˙P (10^{-11} s/s) |
|--------|-------------------------|--------------|--------------------------------|-----------------------------|----------------------------------|-------------------|
| 1806-20 | 1000×                   | No           | No                             | 2 \times 10^{35}            | 7.47 s                            | 2.8               |
| 1900+14 | 1000×                   | 270898       | 5.16 s                         | 3 \times 10^{34}            | 5.16 s                            | 6.1               |
| 0525-66 | 20000×                  | 050379       | 8 s                            | 10^{36-37}                  | No                               | —                 |
| 1627-41 | 400000×                 | No           | No                             | 10^{35}                     | 6.4 s?                           | —                 |
| 1801-23 | ?                       | No           | No                             | ?                           | —                                | —                 |

VII THE MAGNETAR MODEL

Briefly, the magnetar model [6,29] explains the short, soft bursts by localized cracking on the neutron star surface, with excitation of Alfven waves which accelerate electrons. Every 20–100 y, a massive, global crustquake takes place. Regions of the neutron star with magnetic fields of opposite polarity suddenly encounter one another, resulting in magnetic field annihilation and energization of the magnetosphere, giving rise to a giant flare. Magnetars are thought to be born in ~ 1 out of 10 supernova explosions, and remain active for perhaps 10,000 y. Thus there should be about 10 active magnetars in the Galaxy at any given time. So far, we have found 4.5 ± 0.5. Stay tuned for more!

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REFERENCES

1. Atteia, J.-L. et al., Ap. J. 320, L105 (1987).
2. Barat, C. et al., Astron. Astrophys. 79, L24 (1979).
3. Cline, T. et al., Ap. J. 237, L1 (1980).
4. Cline, T. et al., Ap. J., accepted, astro-ph/9909054, (1999).
5. Cooke, B., Nature 366, 413 (1993).
6. Duncan, R., and Thompson, C., Ap. J. 392, L9 (1992).
7. Evans, W. D. et al., Ap. J. 237, L7 (1980).
8. Frail, D. et al., Ap. J. 480, L129 (1997).
9. Frail, D. et al., *Nature* **398**, 127 (1999).
10. Golenetskii, S. et al., *Sov. Astron. Lett.* **5**, 340 (1979).
11. Golenetskii, S. et al., *Sov. Astron. Lett.* **13(3)**, 166 (1987).
12. Hurley, K. et al., *Ap. J.* **510**, L107 (1999a).
13. Hurley, K. et al., *Ap. J.* **523**, L37 (1999b).
14. Hurley, K. et al., *Ap. J.* **510**, L111 (1999c).
15. Hurley, K. et al., *Nature* **397**, 41 (1999d).
16. Hurley, K. et al., *Ap. J.* **519**, L143 (1999e).
17. Hurley, K. et al., *Ap. J.*, in press, astro-ph/9909355 (1999f).
18. Inan, U. et al., *GRL*, in press (1999).
19. Kouveliotou, C. et al., *Nature* **362**, 728 (1993).
20. Kouveliotou, C. et al., *Nature* **393**, 235 (1998).
21. Kouveliotou, C. et al., *Ap. J.* **510**, L115 (1999).
22. Kulkarni, S., and Frail, D., *Nature* **365**, 33 (1993).
23. Mazets, E. et al., *Sov. Astron. Lett.* **5(6)**, 343 (1979).
24. Mazets, E. et al., *Ap. J.* **519**, L151 (1999).
25. Murakami, T. et al., *Nature* **368**, 127 (1994).
26. Paczynski, B., *Acta Astronomica* **42**, 145 (1992).
27. Rothschild, R. et al., *Nature* **368**, 432 (1994).
28. Smith, D. et al., *Ap. J.* **519**, L147 (1999).
29. Thompson, C., and Duncan, R., *Mon. Not. R. Astron. Soc.* **275**, 255 (1995).
30. van Kerkwijk, M. et al., *Ap. J.* **444**, L33 (1995).
31. Vancura, O. et al., *Ap. J.* **394**, 158 (1992).
32. Vasisht, G. et al., *Ap. J.* **431**, L35 (1994).
33. Vasisht, G. et al., *Ap. J.* **440**, L65 (1995).
34. Woods, P. et al., *Ap. J.* **519**, L139 (1999a).
35. Woods, P. et al., *Ap. J.* **519**, 139 (1999b).