UNRAVELING THE COOLING TREND OF THE SOFT GAMMA REPEATER SGR 1627−41

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ABSTRACT

SGR 1627−41 was discovered in 1998 after a single active episode that lasted ~6 weeks. We report here our monitoring results of the decay trend of the persistent X-ray luminosity of the source during the last 5 years. We find an initial temporal power-law decay with index 0.47, reaching a plateau that is followed by a sharp (factor of 10) flux decline ~800 days after the source activation. The source spectrum is best described during the entire period by a single power law with high absorption [$N_H = 9.0(7) \times 10^{22} \text{ cm}^{-2}$]; the spectral index, however, varies dramatically between 2.2 and 3.8 spanning the entire range for all known soft gamma repeater sources. We discuss the cooling behavior of the neutron star assuming a deep crustal heating initiated by the burst activity of the source during 1998.

Subject heading: stars: neutron

1. INTRODUCTION

Soft gamma repeaters (SGRs) are a rare subclass of neutron stars characterized by their emission of randomly recurring outbursts of hard X-rays and soft gamma rays. There are currently four SGRs identified in our galaxy and one in the Large Magellanic Cloud (LMC), three of which have been found to pulse with periods ranging between 5 and 8 s (for a review, see Kouveliotou 2004). The very rapid secular increase of these periods (spin-down of $P \sim 10^{-10} \text{ s}^{-1}$) argues for angular momentum loss from a highly magnetized neutron star ($B \sim 10^{14} \text{ G}$). This idea was developed by Duncan & Thompson (1992, hereafter DT92) and, independently, by Paczyński (1992), following the detection of the most intense high-energy transient observed to date, the giant flare of 1979 March 5 (from SGR 0526−66 in the LMC), which gave a lower limit of the source magnetic field of $\sim 10^{14} \text{ G}$. DT92 dubbed such sources “magnetars.”

SGR 1627−41 was discovered with the Burst and Transient Source Experiment on the Compton Gamma Ray Observatory in 1998 June (Kouveliotou et al. 1998), when it emitted over 100 bursts within an interval of 6 weeks (Woods et al. 1999); no further burst emission has been observed to date (2003 July). Roughly 20% of all events, representing ~98% of the total burst-emitted energy (20–150 keV), were bunched in an interval of three days, 1998 June 15–18. The X-ray counterpart to SGR 1627−41, SAX J1635.8−4736, was discovered in a BeppoSAX/Narrow Field Instrument (NFI) observation on August 7, at $\alpha = 16^\text{h}35^\text{m}49.8^\text{s}$ and $\delta = -47^\circ35'44''$ (J2000.0) with an error circle of radius 1' (95% confidence level; Woods et al. 1999). In S. Wachter et al. (2003, in preparation), we report an improved (error radius $\leq 0.3'$) source location recently derived with the Chandra X-Ray Observatory, together with results of our near-infrared searches for a counterpart. A search for coherent pulsations in the BeppoSAX data set, when the source intensity was higher, showed marginal evidence (~3 $\sigma$ confidence level) near 6.4 s; to date the source spin period remains unknown.

During their quiescent periods, SGRs have been identified as persistent X-ray sources with luminosities of $\sim 10^{34}–10^{35}$ ergs s$^{-1}$. When active, their outbursts last anywhere from days to a year, with different burst frequency and intensity per source and per outburst. SGR bursts have typical durations of 0.1 s, and their spectra are usually best-fitted to an optically thin thermal bremsstrahlung function with $kT \sim 30 \text{ keV}$. The burst size distributions follow a power law of index $−0.6$, with peak luminosities of events ranging from the small common bursts at $\leq 5 \times 10^{37}$ ergs s$^{-1}$ to the rare giant flares (only two have been observed) at $\sim 10^{44}$ ergs s$^{-1}$.

The enhancing effect of the SGR bursting activity on the flux level of their persistent emission is well documented for SGR 1900+14, where the flux was shown to increase by a factor of ~700 after the giant flare of 1998 August 27. The flux from the source decayed within ~40 days according to a power law, $F \propto (t - t_0)^{-0.7}$ (Woods et al. 2001). For the next several months, the burst activity and persistent/pulsed flux level gradually declined. The SGR was not observed to reach its quiescent flux level of $1 \times 10^{31}$ ergs cm$^{-2}$ s$^{-1}$ until 2000 April, approximately 2 years after the burst reactivation of the SGR, although extrapolation of the 40 day decay after 1998 August 27 suggests that it may have done so between observations. The source has been intermittently active ever since, resulting in erratic flux decay behavior.

In contrast, SGR 1627−41 has remained dormant after a single active episode, thus being a better long-term target for SGR cooling studies. We present here (§§ 2, 3, 4, and 5) the results of our monitoring of the flux decay of the quiescent X-ray counterpart of SGR 1627−41 obtained with imaging instruments (BeppoSAX, ASCA, and Chandra) spanning an interval of roughly 5 years. In § 6 we discuss the source’s atypical
decay within the framework of neutron star crust cooling and its implications on the properties of SGR progenitors.

2. BeppoSAX OBSERVATIONS

Since 1998, we have observed the source four times with the BeppoSAX/NFI. Results from the first two observations were presented in Woods et al. (1999). Here, we present results from a refined analysis of the earlier data together with the two subsequent observations in 1999 August and 2000 September. For all BeppoSAX data sets, we followed the data extraction procedure described in Woods et al. (1999). A log of the observations and spectral fit results is given in Table 1. Because of the significant contribution to the background from the Galactic ridge, we are using contemporaneous data from a concentric annulus around our source position for our background spectrum. An energy-dependent multiplicative factor has been applied to the background spectrum to correct for reduced efficiency at off-axis angles in both the LECS and the MECS. From these earlier BeppoSAX observations, in which the higher source intensity allowed for better statistics, we have determined using XSPEC (version 11.2; Arnaud 1996) that, in all cases, a single power-law (PL) model is the best-fit spectral function for the data.

3. ASCA OBSERVATIONS

SGR 1627–41 was observed by ASCA on 1999 February 26–28. On board ASCA are four independent X-ray telescopes and four independent X-ray detectors; the latter are two Gas Imaging Spectrometers (GISs) and two Solid-State Imaging Spectrometers (SISs). For the present analysis, we have extracted all available GIS and SIS data sets and applied the standard screening criteria. We reduced the data separately for each GIS and for each SIS detector in 1 CCD mode and extracted spectra using XSELECT (version 2.1) from circular regions centered on the SGR with radii of 4′ and 2′.6 for GIS and SIS, respectively. Since the source was faint, we used a smaller region than the recommended ASCA source extraction region to reduce the background. Finally, the background was taken from neighboring regions on each detector.

To derive an accurate measure of the source flux, we generated off-axis GIS ancillary response files, dead-time corrected the GIS data, and included only the high and medium bit rate SIS data. We then generated response files (using FTOOLS version 5.2 tasksascaarf and sisrmg) for each detector separately. We combined all the GIS data into a single data set (similarly the GIS data), weighting in each case the response functions by their individual effective live times. We grouped the data into energy channels that contained at least 25 events each.

We performed independent fits to the SIS and GIS data (using XSPEC) of a PL model including the effects of Galactic absorption. We note that the final flux that we measure for the SGR (see also § 5 and Table 1) is significantly lower than the value reported earlier ($F = 5.1 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$) by Hurley et al. (2000). This discrepancy is due to the low source count rate in the GIS detectors, which results in a critical dependence of the measured flux on the selected background region. For example, choosing a background region several arcminutes away from the SGR, where the detector count rate is much lower, we find a flux comparable to the value reported by Hurley et al. (2000). In contrast, we have selected a background region close in angle to the SGR, which resides in an area of the sky that contains significant diffuse emission. This choice is justified by the fact that the flux that we measure with the GIS is in good agreement with the flux measured by the SIS detectors (within 10%), which do not suffer from this issue because of their smaller field of view.

4. CHANDRA OBSERVATIONS

We observed SGR 1627–41 with Chandra on 1999 September 20 (observation 1) and on 2003 March 24 (observation 2). In both observations the SGR fell on ACIS-S3 (operating in Timed Exposure mode), a back-illuminated CCD with good spectral resolution. We used calibration products from Chandra CALDB (version 2.21). Using the standard CIAO (version 2.3) tools, we applied the appropriate gains, CTI corrected the events, and filtered the data to include events with grades $= 0$, $2$, $4$, $6$. We selected a circular extraction region of 3′′ radius centered on the SGR for the source spectra. We collected the background spectrum from annular regions centered on the SGR with inner and outer radius of 3′′ and 30′′, respectively. The 2–10 keV background-subtracted source count rates were 0.0049 counts s$^{-1}$ (observation 1) and 0.0058 counts s$^{-1}$ (observation 2) (the background contributed only $\sim 3\%$ to the total count rate for each observation). We then generated the response files using standard CIAO tools and corrected the ancillary response files to account for the time-dependent degradation of the ACIS quantum efficiency. We have investigated bremsstrahlung, blackbody, and PL models using XSPEC and find that the PL model gives the least C-statistic for both data sets (fitted individually or simultaneously). We have, therefore, adopted the absorbed PL model as the preferred continuum model for the Chandra observations. Our spectral fit results to the ungrouped data using the C-statistic are given in Table 2. A simple ratio of the two data sets indicates that observation 2 has a softer spectrum, as also indicated by the spectra in Table 2.

5. JOINT SPECTRAL ANALYSIS–SOURCE ENERGETICS

In §§ 2–4, each of the seven data sets was fitted independently to a PL model attenuated by interstellar absorption. Motivated by the consistency of the measured spectral parameters from all seven observations, we performed a simultaneous fit to all data sets linking the hydrogen column density, $N_H$. We have kept the value of $N_H$ linked, assuming that there is no obvious physical reason for the intrinsic source absorption to change while the source is in quiescence. For all observations, the fit was statistically acceptable ($x^2/p = 690/655$). We measured the (linked) effective hydrogen column to be $N_H = (9.0 \pm 0.7) \times 10^{22}$ cm$^{-2}$. Table 1 lists all other fit parameters. Figure 1 displays the evolution of the source flux (top) and spectral index (bottom) since its activation. During the first $\sim 800$ days following the 1998 outburst, the flux from SGR 1627–41 decayed monotonically as a power law with exponent.
The last BeppoSAX observation indicated that the source might have reached a plateau, approximately 2 years after activation. However, the two subsequent Chandra observations (at ∼1200 and ∼1500 days after the outburst) are significantly below (almost a factor of 10) the extrapolated decay trend. The photon index does show significant changes in the ~5 years following the 1998 outburst; the probability that the observed variability is due to statistical fluctuations is 7.1 × 10^{-4}. We discuss these results further in the next section.

While the spectra of SGRs 1900+14 and 1806–20 are relatively hard, with indices between 2.0 and 2.5, SGR 0526–66 is much softer, with a spectral index of 3.5. Interestingly, the spectral index range of SGR 1627–41 (2.2–3.8) spans all other SGR sources observed at their quiescent states, although we do not see the blackbody (bb) component observed in SGR 0526–66. This is not unexpected, given that the bb contribution in the unabsorbed flux of 1900 + 14 is of the order of 20%; since the column density along the line of sight for SGR 1627–41 is almost 10 times higher, extreme absorption between 0.1–2.0 keV would hinder the detection of any bb component that contributes less than at least 50% of the (unabsorbed) flux.

Near the source activation the flux was 6.56 × 10^{-12} ergs cm^{-2} s^{-1}, corresponding to a source luminosity of $L = 9.5 \times 10^{34}$ ergs s^{-1} (assuming a source distance of 11 kpc; Corbel et al. 1999). The luminosity decayed slowly to $2.7 \times 10^{34}$ before it plummeted to its current value of $3.9 \times 10^{33}$ ergs s^{-1}. In comparison, the persistent luminosity levels of SGRs 1900+14, 1806–20, and 0526–66 are ∼6 × 10^{34}, 4.1 × 10^{35}, and ∼10^{36} ergs s^{-1}, respectively. If SGR 1627–41 decays further below its current luminosity level, it may well provide the first direct link between SGRs and isolated neutron stars, whose luminosities it seemed to be approaching pretty rapidly through day 1200 (Fig. 1).

6. INTERPRETATION AND DISCUSSION

The study of the afterglow following an SGR episodic energy release is complicated by the fact that both the magnetosphere and the surface are subject to change, and by the unpredictable nature of reheating by additional later bursts. Conventional wisdom, although still somewhat tentative, would suggest that the surface radiation is reprocessed and nonthermalized by resonant scattering in the magnetosphere (Thompson, Lyutikov, & Kulkarni 2002) This suggests that sharp spectral changes would signify changes in the magnetospheric configuration; conversely, an ordered gradual decline in intensity with a constant spectrum indicates a decline in the thermal surface emission. To study the latter, a period of gradual decline is needed uninterrupted by new events that reheat the surface. It was not obvious a priori that all these factors could be unraveled.

The 40 day afterglow following the 1998 August 27 giant flare of SGR 1900+14 was extremely well fitted by a crustal cooling model (Lyubarsky, Eichler, & Thompson 2002, hereafter LET02), despite the existence of many small bursts that took place during that period. Ironically, the luminosity of this source was seen to increase and behave erratically over the following year, when there was relatively little SGR burst activity. In other words, SGR bursts do not necessarily heat the crust significantly, and moreover, there may be other kinds of sporadic heating that are not expressed in SGR bursts.

Encouraged by the success of our outer crust cooling model for the 40 day afterglow of SGR 1900+14, we attempt here to understand the 3 yr monotonic decline of SGR 1627–41 as cooling after a single deep crustal heating event coinciding with the burst activity of 1998. Details of our calculational methods can be found in LET02. In particular, the leveling of the flux during the third year followed by its sharp decline are curious features that beg for an explanation within this model.

We present in Figure 2 our numerical calculations of the temperature evolution (cooling) of the neutron star crust with depth, $z$, assuming an initial energy injection to the crust of the order of $10^{47}$ ergs (estimates of the total energy released in bursts during the activation of SGR 1627–41 range between $4 \times 10^{47}$ and $2 \times 10^{46}$ ergs; here we assume that the conversion efficiency of the total energy released during the activation into soft gamma
in the relatively rapid timescale (a few years) for cooling of
dependently of the low core temperature, and this is reflected
star makes the additional prediction of a thin crust, quite in-
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density, therefore, is high enough at the core to cool it via
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the initial temperature to be near in the lower crust. The
is that it increases with density and then decreases as the nature
of the pairing changes; hence, we put a bump in the initial
specific heat increases with depth, the initial temperature (i.e.,
slowly than the specific heat: thus, in the outer crust, where the
energy density of the deposited heat varies with height more
than the specific heat: thus, in the outer crust, where the
specific heat increases with depth, the initial temperature (i.e.,
immediately after the heating event) declines with depth. In
the inner crust, on the other hand, the specific heat rises even more
rapidly with the onset of neutron drip, but only if these neutrons
are unpaired. (Paired neutrons do not represent new degrees of
freedom because they are condensed into a superfluid.) Below
$T_\text{c}$, the temperature below which neutrons pair, the specific heat
of the crust material is small, and it rises dramatically near $T_\text{c}$
free unpaired neutrons appear. It is thus reasonable to choose
the initial temperature to be near $T_\text{c}$ in the lower crust.
The theoretically predicted behavior of $T_\text{c}$ as a function of density
can vary from one model to the next, but the qualitative feature
is that it increases with density and then decreases as the nature
of the pairing changes; hence, we put a bump in the initial
temperature profile at 400 m < $z$ < 500 m. The exact shape of
the bump is not very important, as it gets washed out before it
affects the surface temperature.

We also assume that the core temperature is very low. This
is justified if the mass of the neutron star exceeds 1.5 $M_\odot$ and
the density, therefore, is high enough at the core to cool it via
the direct Urca process. The assumption of a high-mass neutron
star makes the additional prediction of a thin crust, quite in-
dependently of the low core temperature, and this is reflected
in the relatively rapid timescale (a few years) for cooling of
the inner crust. If our interpretation of the transient cooling is
correct, we thus determine the mass of SGR 1627–41 via two
independent considerations to be above 1.5 $M_\odot$.

The time behavior of the surface luminosity is displayed in
Figure 1 (top), where we have plotted the data points together
with the theoretical curve. It is seen that the plateau between
days 400 and 800 is fitted very accurately. The reason is that
the sharp rise in the specific heat near neutron drip and above
$T_\text{c}$ makes this region in the depth temperature plane a very large
heat reservoir, which keeps the temperature at neutron drip very
stable. The duration of the plateau is determined primarily by
the time required for the inner cooling wave to propagate outward
to the neutron drip point. Most of the heat in the inner crust is
conducted to the center of the star. The surface light curve is
insensitive to many other details of the inner initial temperature
profile, because by the time the surface feels the latter, the spatial
variations within it are largely washed out.

This model is unable, of course, to explain the 2003 March
data point, which showed that the flux did not decay further
and, moreover, showed a softening of the spectrum. One could
argue that the apparent flux “ledge” reflects a persistent baseline
luminosity that is observed only when the star is sufficiently
cool. Other SGRs in fact have larger persistent luminosities,
which are temporarily buried by enhanced transient afterglows
that typically follow major bursting episodes. In the other cases
(such as with SGR 1900+14), the persistent luminosity was
attributed (LET02) to a hot core (temperature $\sim 7 \times 10^7$ K). In
the case of SGR 1627–41, however, the “observed” (based,
for the time being, on only two data points) persistent emission
cannot be attributed to a hot core according to our model: we
calculated that any core hot enough to account for observable
persistent emission at the level of the last two points in Figure
would keep the bottom of the crust warm and thus smear out
the observed sharp ledge in the light curve. Further, the
surface temperature would not have dropped fast enough to
have accounted for the first Chandra data point. However, if
the persistent emission is from a small hot spot at the surface,
it does not affect the cooling of the deep crust and can be
considered superimposed onto the theoretical cooling curve. If
this low-level component is ever found to be pulsed, it would
support our conjecture that the baseline emission is heating at
the surface rather than at finite crustal depth. More closely
spaced and longer observations are certainly needed to establish
the current level and nature of the source emission.

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