An X-ray pulsar with a superstrong magnetic field in the soft γ-ray repeater SGR1806 – 20


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Soft γ-ray repeaters (SGRs) emit multiple, brief (~0.1-s), intense outbursts of low-energy γ-rays. They are extremely rare1—three2–4 are known in our Galaxy and one5 in the Large Magellanic Cloud. Two SGRs are associated6,7 with young supernova remnants (SNRs), and therefore most probably with neutron stars, but it remains a puzzle why SGRs are so different from ‘normal’ radio pulsars. Here we report the discovery of pulsations in the X-ray pulsar SGR1806 – 20, which was first detected as an X-ray source in 199619. SGR1806 – 20 became extremely active between October 1996 and November 1997, when over 40 intense bursts and numerous weaker ones were detected19 with the Burst And Transient Source Experiment (BATSE) on board the Compton Gamma-Ray Observatory (CGRO). We observed SGR1806 – 20 with the Rossi X-Ray Timing Explorer (RXTE) five times between 5 and 18 November 1996, starting five days after the first triggered burst detection with BATSE. (Information on the archival data from RXTE/PCA and ASCA is available at http://heasarc.gsfc.nasa.gov.) During these observations19, the source emitted series of outbursts in a ‘bunching’ mode, never seen before. The intensity of the outbursts, as well as the ‘bunching’ mode, varied significantly: mini-outbursts were interlaced with very intense ones and the rate of bursts varied from burst to burst (S. Dieters et al., manuscript in preparation).

We made a period search of the data after excluding all bursts from the time series. The data were then energy-selected for 2–24 keV X-rays, background subtracted and binned at 0.5-s resolution. The resulting light curve was searched for periodicities between 0.03 and 1 Hz, by calculating a fast-Fourier-transform power spectrum (Fig. 1). The peaks in the spectrum are centred on the fundamental frequency of 0.13375 Hz (period of 7.47655 s) and its first harmonic at 0.26750 Hz. We find no significant power in any other frequency in the searched range. The probability that we detect a signal at the fundamental frequency this strong by chance coincidence is 1 × 10⁻¹⁰ (taking into account the number of trials, 1.9 × 10⁴, and the probability per trial, 5 × 10⁻²⁰).

To determine the fundamental period, all data sets were then corrected to the Solar System barycentre and separately folded at the longest detected period of 7.47655 s, and sub-harmonics thereof. These sub-harmonic folds showed multiple 7.47655-s pulses, which were identical, within statistical errors. We therefore conclude that 7.47655 s is the fundamental period.

To refine our period estimate, we have combined all Proportional Counter Array (PCA) data and used a ‘boot-strapping’ method, where the best period obtained from the shortest data span is used to count cycles and estimate the period over the next longest span of data, and so forth until a consistent period is found over the entire data set. This is achieved by cross-correlating the phase folds from data subsets using our best period estimate and fitting the resulting cross-correlation peaks with a gaussian. The phase offset is then converted to a time difference, a new period is calculated and the procedure is continued for the next (longest) span of data. Our errors in the period and period derivative were estimated by performing Monte Carlo simulations of 25 data sets, whereby we added gaussian noise with the data variance to the bins of each phase fold.

Figure 1 Fast-Fourier-transform power spectrum computed for the combined RXTE/PCA observations of 5/6, 7/13 and 17 November 1996 in the 2–24 keV range. (The data on 18 November contained too many bursts to be useful). The individual powers have been normalized by the average noise level to bring the distribution of noise powers into approximate agreement with the χ² distribution with 2 degrees of freedom. The data were sampled in 0.5-s bins. The 0.13375-Hz pulsed signal and its first harmonic at 0.26750 Hz stand out well above the noise level. The data have been barycentre corrected (using the co-ordinates of the LBV star mentioned in the text for the source position).
We find that a constant period does not fit the pulse arrival times well, and we derived an ephemeris of the pulse arrival times from the minimum in the phase-folded pulse light curve (see Fig. 2):

$$T_{\text{min}}(\text{TJD}) = T_0 + NP + \frac{1}{2} PPN$$

where $T_0$ is the reference time in truncated Julian days (TJD = JD − 2440000.5), $P$ is the pulsar period, $P$ is the period derivative and $N$ is the number of elapsed cycles since $T_0$. We find that $T_0 = 10392.450071037(1)$ (TJD), $P = 7.476551(3)$ s and $P = 2.8(1.4) \times 10^{-11}$ s s$^{-1}$.

Using this ephemeris, the corresponding pulse profile of all the RXTE/PCA data is shown in Fig. 2a. The full amplitude of the pulsed flux is $1.0 \pm 0.2$ counts s$^{-1}$ (between 2 and 24 keV). To estimate the point source count rate, we have folded the spectrum derived$^9$ from the observations of the Japanese satellite ASCA of the persistent X-ray source identified$^8$ with SGR1806 − 20 through the detector response of the RXTE/PCA. It predicts 3.9 counts s$^{-1}$ for a point-like source detected with PCA in the 2–24 keV range; the corresponding pulsed flux amplitude is $\sim 26\%$.

We have searched the archival ASCA data of SGR1806 − 20 for the presence of a periodic signal over a period range that encompassed the original period and possible extrapolations given by our $P$ measurement. A significant signal was found in the 1993 data set (epoch TJD 9275.85) at $7.46851 \pm 0.00005$ s with full amplitude of the pulsed flux $\sim 23\%$. The probability of this peak to appear by chance in the ASCA data is $3.6 \times 10^{-4}$, (taking into account the number of trials, 377, and the probability per trial, 0.9). Figure 2b shows the pulse profile of the ASCA folded light curve. We have a marginal detection of the pulsation in the 1995 data set (7.4738 ± 0.001 s, epoch TJD 10006.72). The ASCA and RXTE/PCA periods are consistent with a long-term average spindown rate, $\dot{P} = (8.3 \pm 0.3) \times 10^{-11}$ s s$^{-1}$. The ASCA detection of the periodicity clearly associates the period with SGR1806 − 20 rather than with a hitherto unknown pulsar within the 1$^\circ$ field of view of the RXTE/PCA.

The period we have found in SGR1806 − 20 is very similar to the 8.0-s period found$^{13}$ in SGR0526 − 66 during a three-minute interval following its extremely strong March 1979 burst. This strongly suggests that the mechanism that produces SGR events is associated with a particular type of slowly rotating neutron stars.

What is the energy source of the SGR quiescence and burst emission? The (unabsorbed) flux (2–10 keV) of the quiescent emission from SGR1806 − 20 measured$^{11}$ with ASCA is $\sim 1 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$. Assuming isotropic emission and a distance$^{14}$ for SGR1806 − 20 of $\sim 14$ kpc, the 2–10 keV luminosity of the source is $L_{\text{SGR}} \approx 2 \times 10^{38}$ erg s$^{-1}$. Similarly, the SGR1806 − 20 burst peak luminosity$^{15}$ (25–60 keV) corresponds to $\sim 10^{40}$ erg s$^{-1}$, which is $\gg 10^7$ times higher than the Eddington luminosity of a neutron star of 1.4 solar masses (1.4 $M_\odot$). Two types of energy sources have been proposed to explain the emission from SGRs: accretion, and energy released by the decay of the magnetic field of a strongly ($\gg 10^{12}$ G) magnetized neutron star, a so-called 'magnetar'. (Rotational energy loss, $E_{\text{rot}}$, is not sufficient to explain the observed X-ray luminosity of SGR1806 − 20. For the observed $P$ and $P$ we find $E_{\text{rot}} \approx 10^{39}$ erg s$^{-1}$, two orders of magnitude below $L_{\text{SGR}}$. As we argue below, the 'magnetar' model is the only one that can account for the observed properties of SGR1806 − 20.)

SGR1806 − 20 has been identified with the SNR G10.0 − 0.3, whose radio morphology is that of a plerion (a synchrotron nebula powered by the relativistic wind of a young pulsar); this suggests that it is centrally powered by a compact source. The X-ray spectrum$^{12}$ of the ASCA persistent source is a power law with photon index 2.2, and hydrogen column density, $N_H = 6 \times 10^{22}$ cm$^{-2}$. It does not show the emission lines commonly seen in SNRs, which shows that the contribution from shocked gas is relatively small and further supports the idea that it is an (X-ray) plerion. In addition, radio observations$^{17}$ of SGR1806 − 20 show varying spatial structure at an angular scale of several arcseconds, perhaps a jet. All the above observations indicate that the SNR is powered by a wind of relativistic particles. Thompson and Duncan$^{18}$ estimate that the particle luminosity, $L_p$, from SGR1806 − 20 is of the order of $10^{37}$ erg s$^{-1}$.

The coincidence of SGR1806 − 20 with an LBV (ref. 18), a rare type of evolved massive star, raises the possibility that the SGR persistent X-ray luminosity is caused by accretion from the LBV stellar wind. Accretion-powered emission, however, can be excluded by the following argument$^{9}$, for reasonable (L. Kaper, personal communication) parameters of the LBV (wind velocity $V_w = 500$ km s$^{-1}$, mass loss rate $\sim 10^{-7} M_\odot$ yr$^{-1}$, radius $\sim 100$ solar radii, and the distance $a$ between the two stars $\gg 10^{13}$ cm): at the accretion radius ($r_{\text{acc}} = 2GM_{\text{NS}} V_w^{-2}$, where $M_{\text{NS}}$ is the neutron...
star mass), the pressure exerted by the relativistic wind powering the plerion \( P_{\text{wind}} = L_\gamma / (4 \pi r^2 c^5) \) is \( 1.2 \times 10^{53} \text{ cm}^{-1} \). This pressure exceeds the stellar wind ram pressure \( (P_{\text{ram}} = \rho_u V_s^2 \approx 25 \text{ dyn cm}^{-2} \) where \( \rho_u \) is the density in the wind) by almost two orders of magnitude. Thus, even if the SGR source were in a binary system with the LBV, accretion is highly unlikely to occur.

The radio data, however, may provide evidence for the orbital period of the system, that could be confirmed with a long-term monitoring of the source with RXTE. Frail et al.\(^1\) report that the jet-like structure associated with the plerion has rotated by 50° over an interval of 1.4 yr. It is possible that this structure is the result of a magnetotail of SGR1806 – 20 produced by the strong wind of the LBV. In such a case, we would expect the system orbital period to be of the order of 10 yr.

This leaves us with the magnetar model. Because in this model rotational losses do operate on the neutron star, we can estimate the spin period of the order of 10 yr will rotate at a period in the 10-s range. Thus, unless rotational losses do operate on the neutron star, we can estimate the spin period of the order of 10 yr.

For SGRs developed by Thompson and Duncan\(^8\). According to these pulsars (only ray pulsars (AXPs)\(^{23–25}\), which are very different from normal binary stars.\(^{122}\) Neutron stars with superstrong magnetic fields may, therefore, constitute a non-negligible fraction of newly formed neutron stars and account for at least part of the discrepancy between the birth rates of core-collapse supernovae and of radio pulsars\(^{26–27}\). Neutron stars with superstrong magnetic fields may, therefore, constitute a non-negligible fraction of newly formed neutron stars and account for at least part of the discrepancy between the birth rates of core-collapse supernovae and of radio pulsars\(^{26–27}\). It is unclear whether these magnetars represent the tail of a very broad neutron-star magnetic-field distribution, or whether they form a separate class of young neutron stars with superstrong magnetic fields.

We point out that the value of \( P \tau > 10^9 \) is typical of the values (only five measured so far) for AXPs. This may suggest that SGRs are the earliest phase in the evolution of magnetars, followed by a phase in which they appear as AXPs.

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**letters to nature**


Acknowledgements. We thank R. Duncan, C. Thompson and M. Finger for discussions.

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