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 rare[1]—three[2–4] are known in our Galaxy and one[5] in the Large Magellanic Cloud. Two SGRs are associated[5–7] 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 persistent X-ray flux of SGR1806 − 20, with a period of 7.47 s and a spindown rate of 2.6×10^{-3} s yr^{-1}. We argue that the spindown is due to magnetic dipole emission and find that the pulsar age and (dipolar) magnetic field strength are ~1,500 years and 8×10^{14} gauss, respectively. Our observations demonstrate the existence of 'magnetars', neutron stars with magnetic fields about 100 times stronger than those of radio pulsars, and support earlier suggestions[8,9] that SGR bursts are caused by neutron-star 'crust-quakes' produced by magnetic stresses. The 'magnetar' birth rate is about one per millennium—a substantial fraction of that of radio pulsars. Thus our results may explain why some SNRs have no radio pulsars.

SGR1806 − 20 became extremely active between October 1996 and November 1997, when over 40 intense bursts and numerous weaker ones were detected[10] 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 observations[11], 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 bunch to bunch (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^{-13} (taking into account the number of trials, 1.9×10^6, 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.

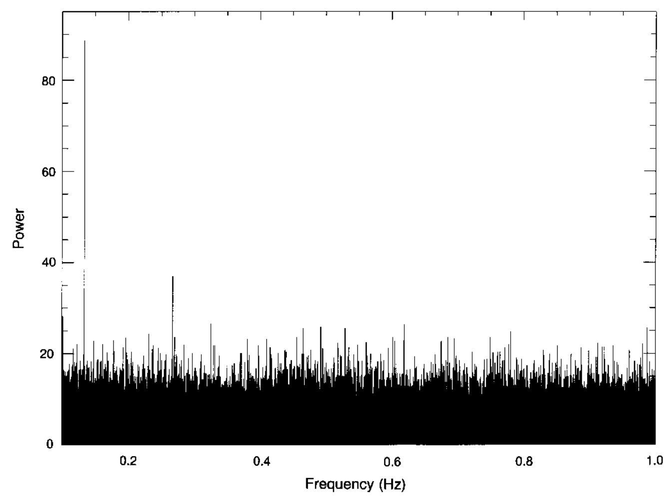

Figure 1 Fast-Fourier-transform power spectrum computed for the combined RXTE/PCA observations of 5/6, 7, 13 and 17 November 1996 in the 2–24 keV range. (The data on 18 November contained too many bursts to be useful). The individual powers have been normalized by the average noise level to bring the distribution of noise powers into approximate agreement with the χ^2 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):

$$T_{\min}(\mathrm{TJD}) = T_0 + NP + \frac{1}{2}P\dot{P}N^2$$

where T_0 is the reference time in truncated Julian days (TJD = JD − 2440000.5), P is the pulsar period, $\dot{P}$ 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 $\dot{P} = 2.8(1.4) \times 10^{-11}$ 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 ± 0.2 counts s^{-1} (between 2 and 24 keV). To estimate the point source count rate, we have folded the spectrum derived[12] from the observations of the Japanese satellite ASCA of the persistent X-ray source identified[6] 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 ~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 $\dot{P}$ measurement. A significant signal was found in the 1993 data set (epoch TJD 9275.85) at 7.46851 ± 0.00025 s with full amplitude of the pulsed flux ~23%. The probability of this peak to appear by chance in the ASCA data is 3.6×10^{-4}, (taking into account the number of trials, 377, and the probability per trial, 9.66×10^{-7}). 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° 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 5 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[12] with ASCA is $\sim 1 \times 10^{-11}$ erg cm^{-2} s^{-1}. Assuming isotropic emission and a distance[14] for SGR1806 − 20 of ~14 kpc, the 2–10 keV luminosity of the source is $L_{\mathrm{SGR}} \approx 2 \times 10^{35}$ erg s^{-1}. Similarly, the SGR1806 − 20 burst peak luminosity[15] (25–60 keV) corresponds to $\sim 10^{41}$ erg s^{-1}, which is $\gtrsim 10^3$ 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 ($\gtrsim 10^{14}$ G) magnetized neutron star, a so-called[8] 'magnetar'. (Rotational energy loss, $\dot{E}_{\mathrm{rot}}$, is not sufficient to explain the observed X-ray luminosity of SGR1806 − 20. For the observed P and $\dot{P}$ we find $\dot{E}_{\mathrm{rot}} \approx 10^{33}$ erg s^{-1} two orders of magnitude below L_{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 G 10.0 − 0.3, whose radio morphology is that of a plerion[16] (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, $N_{\mathrm{H}} = 6 \times 10^{22}$ 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[9] 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 $V_{\mathrm{w}} \approx 500$ km s^{-1}, mass loss rate $\sim 10^{-5} M_\odot$ yr^{-1}, radius ~100 solar radii, and the distance a between the two stars $\gtrsim 10^{13}$ cm): at the accretion radius ($r_{\mathrm{acc}} = 2GM_{\mathrm{NS}}V_{\mathrm{w}}^{-2}$, where M_{NS} is the neutron

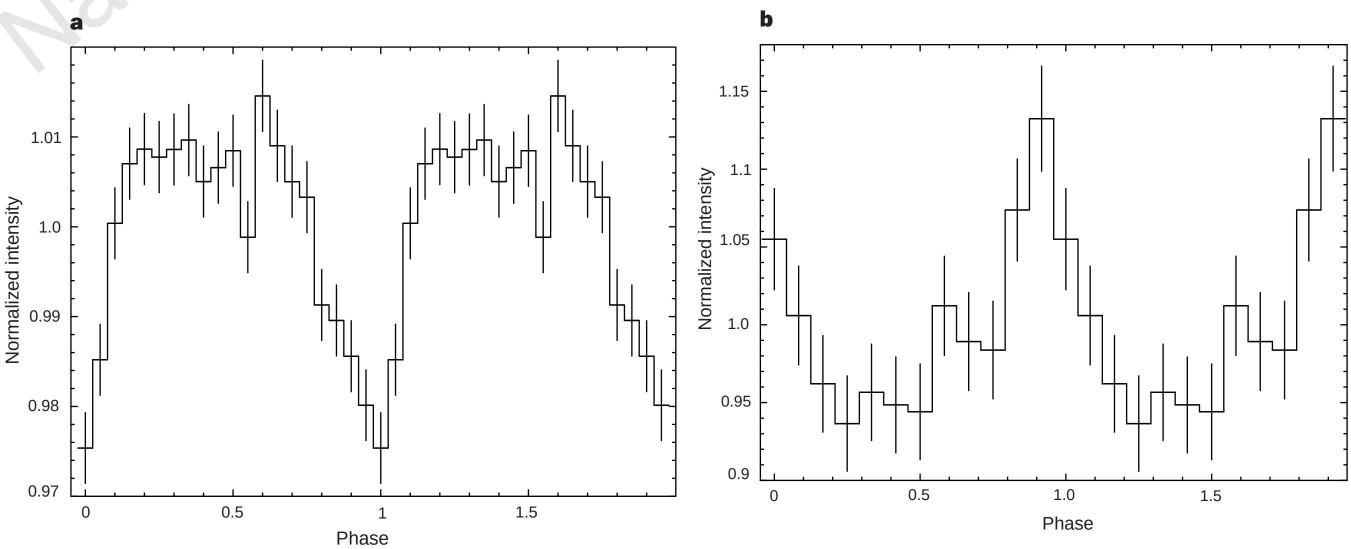

Figure 2 Epoch folded pulse profiles of SGR1806 – 20. **a**, RXTE/PCA data in 20 phase bins at the fundamental period of 7.476551 s, between 2 and 24 keV. **b**, ASCA data (from the 1993 observation of SGR1806 – 20) in 12 phase bins (to increase the signal to noise ratio) at the fundamental period of 7.4685125 s between 2 and 10 keV. The plots in the two panels cover two periods, for clarity. The ASCA pulse profile is not derived by extrapolation of the RXTE/PCA period and period derivative; it is found by independent period searches.

star mass), the pressure exerted by the relativistic wind powering the plerion $P_{\rm wind} = L_{\rm p}/(4\pi c r_{\rm acc}^2)$ is $1.2 \times 10^3\,{\rm dyn\,cm^{-2}}$. This pressure exceeds the stellar wind ram pressure ($P_{\rm ram} = \rho_{\rm w} V_{\rm w}^2 \lesssim 25\,{\rm dyn\,cm^{-2}}$, where $\rho_{\rm w}$ 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.*[17] 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 spindown pulsar age, τ, and magnetic field, B, from its period and period derivative, according to[19]: $\tau = P/2\dot{P}$ and $B = 3.2 \times 10^{19}\sqrt{P\dot{P}}$, respectively. Substituting the above values for P and for the long-term $\dot{P}$ we find $\tau \approx 1{,}500$ yr and $B \approx 8 \times 10^{14}$ G. Thompson and Blaes[20] have shown that these formulae are of approximate validity only when the particle luminosity from a neutron star is much lower than its standard magnetic dipole luminosity. In particular, when the particle pressure is high enough to exceed the dipole pressure inside the light cylinder of the neutron star, the magnetic field lines will be combed out beyond a radius $R_{\rm p}$, where $R_{\rm p}/R_{\rm NS} \approx (B_{\rm D}^2 R_{\rm NS}^2 c/2L_{\rm p})^{1/4}$. Here $B_{\rm D}$ and $R_{\rm NS}$ are the dipole magnetic field and the neutron star radius, respectively. This raises the magnetic field strength at the light cylinder, and therefore the magnetic dipole torque. Following their analysis, we find for the magnetic field and spindown age of SGR1806 − 20, $\sim 2 \times 10^{14}$ G and ~8,000 yr, respectively. The latter value is in good agreement with an earlier age estimate[16] of ~10,000 yr for G 10.0 − 0.3 based on angular diameter versus surface brightness argument.

The magnetic field value is the highest measured so far (its uncorrected value is similar to that estimated[21] for GB790305 and for[22] 1E 1841 − 045 in the young SNR Kes 73); it supports the model for SGRs developed by Thompson and Duncan[8]. According to these workers, the SGR bursts are triggered by cracking of the neutron-star crust caused by magnetic stresses, which leads to sudden injection of Alfvén waves into the magnetosphere, particle acceleration, and formation of an optically thick pair plasma. Very high magnetic fields would explain the super-Eddington luminosities of SGRs, by suppressing the electron scattering cross-section of photons by a factor $\propto B^{-2}$. In addition, the decay of the magnetic field heats the neutron-star interior, giving rise to persistent thermal soft X-ray emission from the surface. Superstrong fields also lead to rapid spindown of a neutron star, which after a time interval of the order of 10^4 yr will rotate at a period in the 10-s range. Thus, unless G 10.0 − 0.3 is not a plerionic SNR, the conclusion that SGR1806 − 20 is a magnetar seems unavoidable.

SGRs have several striking similarities with a small group of X-ray pulsars (only ~6 sources are known so far), called 'anomalous' X-ray pulsars (AXPs)[23–25], which are very different from normal binary X-ray pulsars, with respect to their spin period distribution (all between 6 and 12 s), their very soft X-ray spectra, and the absence of evidence for a binary companion. Several AXPs are associated with young SNRs; their very small distances to the galactic plane shows that AXPs are likewise recently formed neutron stars[24]. Non-detection of orbital Doppler shifts in their X-ray pulsations indicates that if they have companions, these must be very low-mass stars.

The accretion model of AXPs fails to explain the narrow distribution of their observed pulse periods and X-ray luminosities. In the magnetar model the observed limited period range reflects that the age range of AXPs is limited, and that for magnetic-dipole spindown the spin period varies rather slowly with time t as $t^{1/2}$. For a particular model of the B-field decay. Thompson and Duncan[9] find for the period $P \approx (9\,{\rm s}) B_{15} R_6^2 M_{1.4}^{-1/2} (t/10^4\,{\rm yr})^{-1/2}$ and the X-ray luminosity $L_{\rm X} \approx 5 \times 10^{34} (t/10^4\,{\rm yr})^{-1/3}\,{\rm erg\,s^{-1}}$ (the latter expression depends somewhat on details of the neutron star equation of state). Here $B_{15} = B/10^{15}$G, $R_6 = R_{\rm NS}/10^6$ cm, and $M_{1.4} = M_{\rm NS}/1.4\,M_\odot$ The observed X-ray luminosities and spin periods therefore follow naturally from the model.

According to a previous[1] analysis, the total number of SGRs in our galaxy is $\lesssim 7$. If the age estimate of SGR1806 − 20 is typical for these objects, their birth rate is of the order of one per millennium, that is, ~10% of the birth rate of normal 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[28]. 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 $P/\dot{P}$ of SGR1806 − 20 is smaller than any 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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