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Timing Noise in SGR 1806-20

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ABSTRACT

We have phase connected a sequence of *Rossi X-ray Timing Explorer* Proportional Counter Array observations of SGR 1806−20 covering 178 days. We find a simple secular spin-down model does not adequately fit the data. The period derivative varies gradually during the observations between 8.1 and 11.7 $\times$ 10^{-11} s s^{-1} (at its highest, $\sim$40% larger than the long term trend), while the average burst rate as seen with the Burst and Transient Source Experiment drops throughout the time interval. The phase residuals give no compelling evidence for periodicity, but more closely resemble timing noise as seen in radio pulsars. The magnitude of the timing noise, however, is large relative to the noise level typically found in radio pulsars ($\Delta_8 = 4.8$; frequency derivative average power $\approx 7 \times 10^{-20}$ cyc^2 s^{-3}). Combining these results with the noise levels measured for some AXPs, we find all magnetar candidates have Δ_8 values larger than those expected from a simple extrapolation of the correlation found in radio pulsars. We find that the timing noise in SGR 1806−20 is greater than or equal to the levels found in some accreting systems (e.g., Vela X−1, 4U 1538−52 and 4U 1626−67), but the spin-down of SGR 1806−20 has thus far maintained coherence over 6 years. Alternatively, an orbital model with a period $P_{\rm orb} = 733$ days provides a statistically acceptable fit to the data. If the phase residuals are created by Doppler shifts from a gravitationally bound companion, then the allowed parameter space for the mass function (small) and orbital separation (large) rule out the possibility of accretion from the companion sufficient to power the persistent emission from the SGR.

Subject headings: stars: individual (SGR 1806-20) — stars: pulsars — X-rays: bursts

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1. Introduction

The soft gamma repeater (SGR), SGR 1806−20 is one of four known SGRs or sources of brief (∼0.1 s), intense ($\lesssim 10^{42}$ ergs s^{-1}) hard X-ray/soft γ-ray burst emission (for a review, see Hurley 2000 and Woods 2000). All of the SGRs have persistent X-ray counterparts that are positionally coincident with young ($\sim 10^4$ yr) supernova remnants. Two SGRs (1806−20 and 1900+14) are also X-ray pulsars that have been found to spin down at a rapid rate (Kouveliotou et al. 1998; Hurley et al. 1999; Kouveliotou et al. 1999). The physical interpretation for this rapid spin-down has been proposed to be magnetic braking of a strongly magnetized neutron star, or 'magnetar' (Kouveliotou et al. 1998, 1999). The magnetar theory was first developed to explain the extraordinary burst emission from the SGRs (Duncan & Thompson 1992; Paczyński 1992; Thompson & Duncan 1995), and later extended to include a second class of rare X-ray sources, the so-called anomalous X-ray pulsars (AXPs; Thompson & Duncan 1996).

Thompson & Duncan noted that the AXPs have a number of characteristics (with the exception of burst emission) that are similar to the SGRs (see Mereghetti 2000 for a review of AXPs). The AXPs and SGRs have fairly steady X-ray luminosities ($\sim 10^{35}$ ergs s^{-1}). The persistent spectra of most AXPs and SGR 1900+14 (Woods et al. 1999a) are well represented by a two-component (blackbody + power-law) model. The pulse periods of both groups fall within a narrow range (5 – 12 s) and are observed to spin down at rapid rates ($\sim 10^{-12} - 10^{-10}$ s s^{-1}). For three AXPs (4U 0142+61, 1E 2259+586, 1E 1048.1−5937), the spin-down is dominated by a secular component, but shows small, yet significant deviations from this linear trend. Heyl & Hernquist (1999) have estimated the noise level within the frequency histories covering more than 10 years for each of these AXPs. They find that the timing noise levels of these AXPs are consistent with an extrapolation of the correlation found between timing noise and spin-down rate present in radio pulsars (Arzoumanian et al. 1994). Kaspi, Chakrabarty & Steinberger (1999) have recently analyzed an extended sequence of *Rossi X-ray Timing Explorer (RXTE)* Proportional Counter Array (PCA) observations of two AXPs (1E 2259+586 and 1RXS J1709−40). For each source, they were able to phase-connect the data over a two year time span. They found that the spin-down was fairly constant, although, the residuals did show some marginally significant timing noise (i.e. a third-order phase term).

Similar to the aforementioned AXPs, recent work has shown that SGR 1900+14 does not spin down at a constant rate either (Kouveliotou et al. 1999; Woods et al. 1999a; Marsden et al. 1999; Woods et al. 1999b). In the magnetar model, the SGRs are seismically active neutron stars, and there are a few possible sources of spindown variations. The relative strengths of the conduction current and the displacement current in the outer magnetosphere will be modified by bursting activity: both by direct ejection of particles, and by the rearrangement of the surface magnetic field (Thompson et al. 1999). The resulting increase in the spindown torque could be significant for a slowly rotating neutron star, if the magnetic dipole were (approximately) aligned with the rotation axis. Alternative possibilities include enhanced angular momentum loss due to persistent emission of Alfvén waves and particles (Thompson & Blaes 1998; Harding, Contopoulos,

& Kazanas 1999); and long-period precession driven by the asymmetric inertia of the corotating magnetic field (Melatos 1999) or by crustal fractures (Thompson et al. 1999).

Alternatively, the variable spindown of the SGRs has been ascribed to an enhanced propeller or accretion torque acting on more conventional magnetic fields ($B_{\rm dipole} \sim 10^{11} - 10^{12}$ G), by several authors. Marsden et al. (1999, 2000) suggest that the SGRs are neutron stars born with large kick velocities in a dense inter-stellar medium (ISM). In such a situation, the neutron star may catch up with the slowing ejecta, but accretion at the rate inferred from the luminosities of these sources requires a small relative motion (< 10 km s^{-1}). Van Paradijs et al. (1995) earlier proposed that the AXPs are surrounded by fossil disks, left over from the evolution of Thorne-Żytkow objects (TŻO). The TŻOs are compact objects that have entered the stellar envelope of their companion and spiraled into the center (Thorne & Żytkow 1977). A variant of this model, involving fallback disks formed during the early dynamical evolution of supernova, was recently applied to the SGRs by Chatterjee, Hernquist, & Narayan (1999) and Alpar (1999). While these scenarios plausibly account for the observed timing noise, the relation between accretion and the hyper-Eddington SGR flares (in particular the intense $L \sim 10^7\, L_{\rm Edd}$ gamma-ray spikes of the giant flares) remains largely mysterious.

Until now, the spin history of SGR 1806−20 was composed of three widely spaced period measurements covering three years (Kouveliotou et al. 1998). Here, we have phase connected a long sequence of *RXTE*-PCA observations between 1999 February 12 and 1999 August 8. We find that superposed on the dominant quadratic trend in the phases (spin-down term) are significant residuals, i.e., timing noise. We quanitify the level of timing noise and compare it to the levels found in AXPs, magnetically braking radio pulsars, and accreting pulsars. We place limits on any periodicities in the phase residuals and constrain the orbital parameters of any potential companion.

2. Timing Analysis

Between 1999 February 12 and 1999 August 8, SGR 1806−20 was routinely observed with the PCA aboard *RXTE* for a total of 322 ks. The monitoring campaign started with a 50 ks exposure, followed by twenty-two 10 ks observations whose spacing grew from 0.5 days to 7 days where it remained until August. Near the end of the observing sequence, the intervals between observations gradually became shorter and terminated with another 50 ks observation. For each observation, we avoided intervals with clear burst emission, extracted 2 – 10 keV photons, and binned them at 0.125 s time resolution. We barycenter corrected the bin times and performed an epoch-fold search (7.480 s − 7.485 s) on the data about the period predicted from the spin-down measured by Kouveliotou et al. (1998). The initial ∼50 ks of data were folded on the frequency with the largest χ^2 value from the epoch-fold search in order to create a template profile. We then folded individual 3 – 11 ks segments of the same data on this frequency. A fast Fourier transform was applied to the folded profiles of both the individual segments and the net template

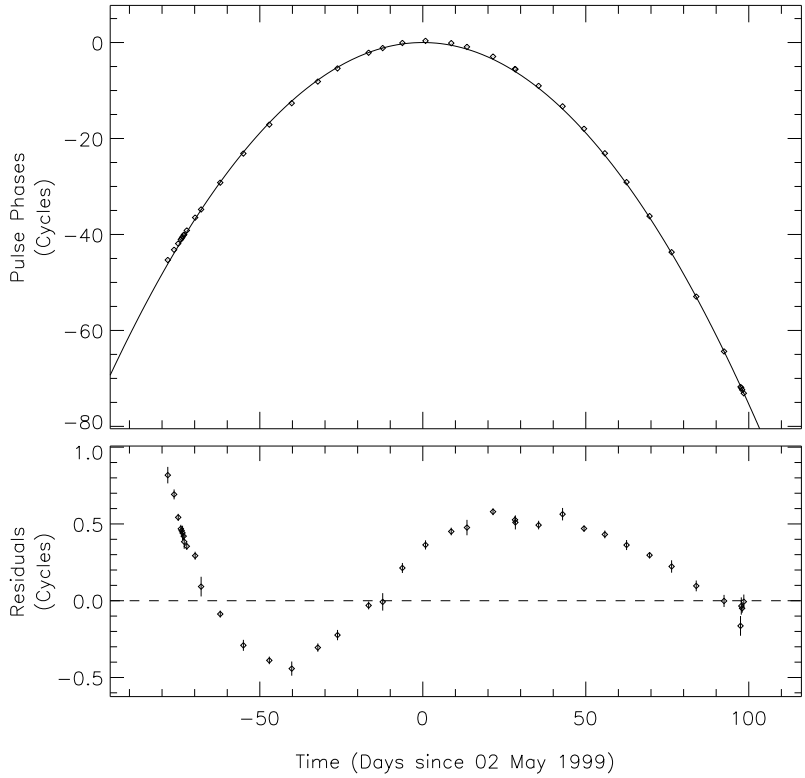

Fig. 1.— Pulse phases for SGR 1806−20 during 1999 minus a linear trend *(top)* and minus a quadratic *(bottom)*.

profile. Using the first four harmonics of the Fourier representation of the profiles, the individual profiles were cross-correlated with the template profile yielding the relative phase, and intensity of each segment. A new ephemeris was obtained by fitting these phases to a polynomial of the form $\phi(t) = \phi_0 + \nu\,(t-t_0) + \frac{1}{2}\dot{\nu}\,(t-t_0)^2 + \frac{1}{6}\ddot{\nu}\,(t-t_0)^3 + \ldots + \frac{1}{n!}\nu^{(n)}\,(t-t_0)^n$, where $\phi(t)$ is the phase, ϕ_0 is a phase offset, t_0 is the epoch, ν is the frequency, $\dot{\nu}$ is the frequency derivative, $\ddot{\nu}$ is the second time derivative of the frequency, and $\nu^{(n)}$ is the $n^{\rm th}$ derivative of the frequency. This procedure was iterated, each time using a revised template profile determined from the previous data set. As more data were gradually included in the analysis, the addition of higher order polynomials became necessary to obtain an adequate fit to the phases (see Figure 1). When the entire data set was fit, we were able to determine the frequency and the first three derivatives (the detection of the $4^{\rm th}$ frequency derivative is marginal; see Table 1 for all fitted parameters). Throughout this sequence of observations, the pulsed intensity remained constant.

In order to directly compare with the 1996 PCA observations of SGR 1806−20 (Kouveliotou et al. 1998), we applied the same technique to the 1996 data and measured a frequency and

frequency derivative (see Table 1). These values are consistent with those found by Kouveliotou et al. (1998). The temporal baseline of these data is much shorter (13 days) than the 1999 observations, and so, timing noise of the same magnitude as that found in 1999 is undetectable. The pulse profile (2 – 10 keV) generated from the 1996 observations is very similar to the 2 – 24 keV profile shown in Kouveliotou et al. (1998), having a single broad peak with a narrow valley. The pulse profile in 1999 is similar in that it only shows one peak, however, the width of the valley at this epoch is slightly broader than the peak.

Combining our results with the *ASCA* results reported in Kouveliotou et al. (1998), we construct a period history of SGR 1806−20 over 6 years (Figure 2). We have also performed an off-line search for untriggered events in the BATSE data using the methodology described in Woods et al. (1999b). Plotted along with the period history is the burst rate history as seen with BATSE (Figure 2). To demonstrate the non-uniformity of the period derivative, we plot an exploded view of the period derivative versus time during the 1999 observations.

Motivated by the techniques applied to other pulsars in estimating timing noise, we calculated a power-density spectrum of the frequency derivative residuals and the Δ_8 value for SGR 1806−20. Using the method described by Deeter & Boynton (1982) for unevenly sampled data, we obtained a spectrum for the frequency derivative residuals. We detect significant power in the range 0.3 – 4 $\times$ 10^{-7} Hz at an average level of $\approx 7 \times 10^{-20}$ cyc^2 s^{-3} and consistent with being a flat spectrum. An alternative method to estimate the level of timing noise in a pulsar is to calculate the $\Delta(t)$ parameter ($\Delta(t) \equiv \log \frac{|\ddot{\nu}|t^3}{6\nu}$ [Arzoumanian et al. 1994]). In order to compare our results to those of Arzoumanian et al., we calculated Δ_8 or $\Delta(10^8)$ for SGR 1806−20. Taking the average $\ddot{\nu}$ over the span of the data ($\langle|\ddot{\nu}|\rangle \approx 5.1 \times 10^{-20}$ Hz s^{-2}), we find $\Delta_8 = 4.8$ for SGR 1806−20. Figure 3 displays the Δ_8 values for 139 radio pulsars (Arzoumanian et al. 1994), 4 AXPs (Heyl & Hernquist 1999; Kaspi et al. 1999), 2 accreting X-ray pulsars (Chakrabarty 1996), and SGR 1806−20. All measurements of Δ_8 for the AXPs and SGR 1806−20 are positioned above an extrapolation of the trend found for the radio pulsars. The 2σ upper limit of 1E 2259+586 from Kaspi et al. is consistent with the trend.

If the timing noise is instead a product of Doppler shifts due to a binary companion, we can fit the phase residuals to an orbit. To do so, we assume a constant period derivative equal to the long-term trend given by a fit to the period measurements ($\dot{P} \sim 8.47 \times 10^{-11}$ s s^{-1}). For this analysis, we used both the phases from the 1996 and 1999 *RXTE* observations as well as the frequency measurements from the earlier *ASCA* observations given by Kouveliotou et al. (1998). We fit these data to an array of orbits with fixed periods between 10 and 5000 days, allowing for a cycle slip between the separate observations. The reduced χ^2 reaches a minimum value of 1.3 at an orbital period $P_{\rm orb} = 733 \pm 14$ days. For this best fit period, we find a mass function $f(M) \approx 8.8 \times 10^{-2}\ M_\odot$ and an orbital separation $A_{\rm x} \sin i \approx 360$ lt-s. There is also a secondary minimum in χ^2 at $P_{\rm orb} \approx 380$ days ($\chi^2_\nu = 1.7$) that is only marginally less favorable than the 733 day orbit.

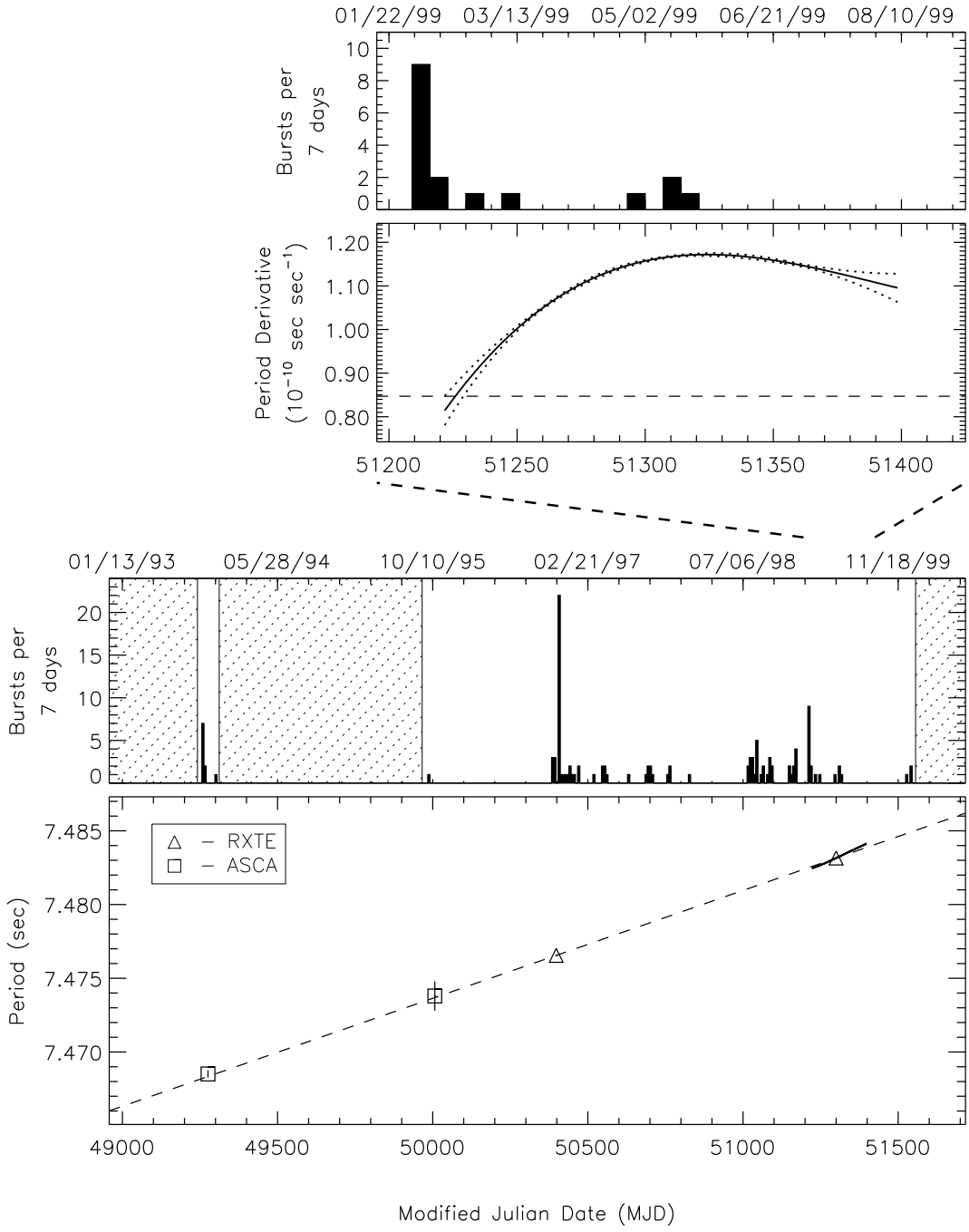

Fig. 2.— *Bottom* – Burst rate history *(upper panel)* and period history *(lower panel)* of SGR 1806−20 from 1993 September through 1999 August. Lower axis label is Modified Julian Date and upper axis is mm/dd/yy. Shaded regions denote intervals where an off-line burst search was not performed and no triggered events were recorded. The dashed line indicates a least squares fit to the period measurements. *Top* – Inset of lower figure showing burst rate history *(upper panel)* and period derivative history *(lower panel)* of SGR 1806−20 during the 1999 observations with the PCA. The dotted lines represent $\pm 2\sigma$ errors on the period derivative. The dashed line is the long-term spin-down rate.

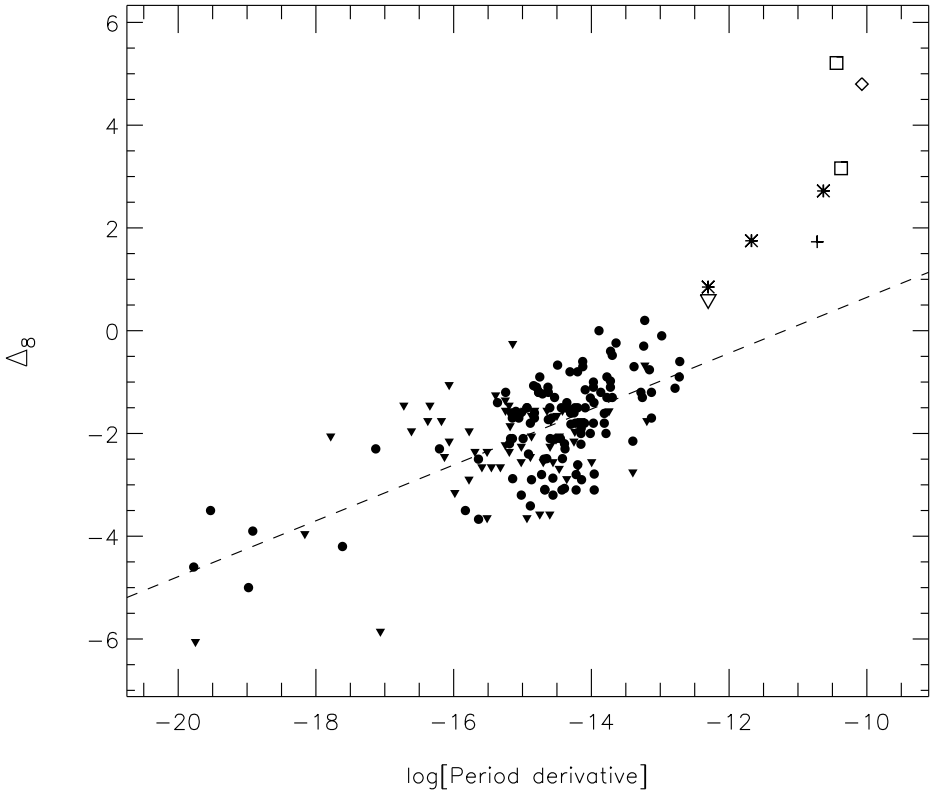

Fig. 3.— The timing noise parameter, Δ_8, plotted versus the period derivative for 139 radio pulsars, 2 accreting X-ray pulsars, 4 AXPs, and one SGR. The filled circles are measurements of Δ_8 and the inverted, filled triangles are upper limits, both for the radio pulsars (Arzoumanian et al. 1994). The asterisks denote measurements of Δ_8 from frequency measurements of three AXPs (Heyl & Hernquist 1999). The inverted, open triangle denotes a 2σ upper limit of Δ_8 for 1E 2259+586, and the plus sign is the Δ_8 value of 1RXS J1709−40 based upon a 4σ detection of $\ddot{\nu}$ (Kaspi et al. 1999). The diamond marks Δ_8 for SGR 1806-20. For comparison, Δ_8 values of two accreting systems, GX 1+4 and 4U 1626−67 (Chakrabarty 1996), are also shown (squares). The dashed line represents a least squares fit to the radio pulsar measurements only (i.e. excluding upper limits). Please note that 43 radio pulsars (see Arzoumanian et al. 1994) and one AXP (1E 2259+586) have duplicate entries.

3. Discussion

We have shown that SGR 1806−20 exhibits strong timing noise during its rapid spindown. The amplitude of the torque variations is significantly higher than in recent measurements of the AXPs 1E 2259+586 and 1RXS J1709−40 by Kaspi et al. (1999), and lies well above the trend

established by Arzoumanian et al. (1994) for radio pulsars. The noise could, in principle, be caused by orbital Doppler shifts, variations in magnetospheric current flows driven by magnetic activity in a magnetar, stellar precession, or variations in the torque from an accretion disk. The noise in SGR 1806−20 does not appear to be predominantly due to glitches.

If the spin frequency variations of SGR 1806−20 are due to a gravitationally bound companion, then the stars must be widely separated and the companion mass ($M_{\rm c}$) must be small ($0.74\ M_\odot < M_{\rm c} < 1.7\ M_\odot$ for an inclination angle $i > 10^\circ$ and an assumed $1.4\ M_\odot$ neutron star). For this particular orbital solution, accretion from the companion can be excluded as the energy source powering the persistent X-ray emission (i.e., $\dot{M} \ll 10^{15}$ g s^{-1}). Alternatively, one may conjecture that the SGR is accreting from a circumstellar disk (Chatterjee et al. 1999; Alpar 1999), or perhaps from co-moving ejecta/ISM material (Marsden et al. 2000). The magnitude of the timing noise in SGR 1806−20 is larger than any known radio pulsar, yet falls within the boundaries of accreting X-ray pulsars (see Figure 2). Over a similar frequency range (see Table 5 of Bildsten et al. 1997), the accreting systems Vela X−1, 4U 1538−52 and 4U 1626−67 have average power levels of 2.2, 1.7, and $\sim 0.1 \times 10^{-20}$ cyc^2 s^{-3}. Accretion models can account for the frequency derivative variations as due to torque fluctuations from interactions between the stellar magnetic field and the surrounding material. Torque fluctuations may then lead to variations in the source luminosity (Ghosh & Lamb 1979; see also Bildsten et al. 1997 for observational evidence that suggests the torque/luminosity relationship may be more complicated), however, the pulsed intensity of SGR 1806−20 remained constant throughout this interval. Furthermore, an important difference between these accreting systems and SGR 1806−20 is that the accreting systems have shown extended intervals of spin-up (Bildsten et al. 1997), whereas SGR 1806−20 and all other SGRs and AXPs have not.

Variations in spin-down are not, however, limited to accreting neutron stars. Timing noise is present in isolated radio pulsars, and is strongest in the youngest members of that population (Cordes & Helfand 1980; Arzoumanian et al. 1994). One of the key premises of the magnetar model is that the SGRs are young and seismically active, with their recurrent outbursts being triggered by energetic fractures of the neutron star crust (Thompson & Duncan 1995). Seismic activity in any magnetized neutron star can modify the external torque through the production of an outward flowing relativistic wind (Thompson & Blaes 1998); or by increasing the conduction current relative to the displacement current in the outer magnetosphere (Thompson et al. 1999). For example, a mass as large as $\Delta M \sim B_{dipole}^2 R_{NS}^6 \Omega^{4/3}/4\pi(GM_{NS})^{5/3} = 2 \times 10^{20}\ (B_{dipole}/4 \times 10^{14}\ {\rm G})^2\ (P/8\ {\rm s})^{-4/3}$ g can be suspended in the outer magnetosphere by centrifugal forces, and can easily be supplied through hyper-Eddington bursting activity. It is not surprising then to find a high level of timing noise in SGR 1806−20, compared with radio pulsars. Furthermore, the strength of the timing noise in SGR 1806−20 relative to the AXPs provides a strong hint that torque variations in an isolated, highly-magnetized neutron star are correlated, perhaps indirectly, with activity as a burst source.

Long period precession has been suggested as a source of spindown variations in magnetars.

Melatos (1999) proposed that precession would be driven by the asymmetric inertia of the external magnetic field, coupled to the hydromagnetic distortion of the star. Alternatively, free precession (of a lower amplitude) could be excited by bursting activity (Thompson et al. 1999). However, a precession period $\tau_{\rm pr}$ requires that the moment of inertia of the *pinned* crustal superfluid does not exceed $I_{pinned}/I_{NS} \sim P/\tau_{\rm pr} = 3 \times 10^{-7}\,(\tau_{\rm pr}/1\ {\rm yr})^{-1}\,(P/8\ {\rm s})$ (Shaham 1977), several orders of magnitude smaller than is inferred for young, glitching pulsars. Thus far, there is no compelling evidence that shows the observed spin-down variations are periodic. Further monitoring of the pulse frequency is required to demonstrate otherwise.

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Table 1. Pulse ephemeris for SGR 1806−20 from *RXTE* PCA observations.

Parameter	1996 November 05 – 18	1999 February 12 – August 8
Epoch (MJD)	50398	51300
Exposure (ksec)	133.5	322.2
χ^2/dof	1.8/8	55.4/33
ν (Hz)	0.133751469(20)	0.133633498(5)
$\dot{\nu}$ (10^{-12} Hz s^{-1})	-1.22(17)	-2.0666(27)
$\ddot{\nu}$ (10^{-20} Hz s^{-2})	...	-2.64(19)
$\nu^{(3)}$ (10^{-26} Hz s^{-3})	...	1.47(7)
$\nu^{(4)}$ (10^{-33} Hz s^{-4})	...	-1.9(6)
P (s)	7.4765534(12)	7.48315368(29)
$\dot{P}$ (10^{-11} s s^{-1})	6.8(10)	11.572(15)