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PRECISE *CHANDRA* LOCALIZATION OF THE SOFT GAMMA-RAY REPEATER SGR 1806−20

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ABSTRACT

We present observations of the soft γ-ray repeater SGR 1806−20 taken with the *Chandra X-Ray Observatory*. We identify the X-ray counterpart of SGR 1806−20 based on detection of 7.5 s pulsations. Using three unrelated X-ray sources (and USNO stars) as position references, we are able to determine that the SGR is at $\alpha_{2000} = 18^h08^m39^s.32$ and $\delta_{2000} = -20°24'39''.5$, with rms uncertainty of 0″.3 in each coordinate. We find that SGR 1806−20 is located within the 1 σ error region determined by Interplanetary Network data and is $14'' \pm 0''.5$ distant from the nonthermal core of SNR G10.0−0.3, excluding SGR 1806−20 as the origin of the core. We see evidence of a significant deviation of the spin-down of SGR 1806−20 from its long-term trend, demonstrating erratic spin-down behavior in this source similar to that seen in other SGRs. Finally, we show that there is a broad X-ray halo surrounding SGR 1806−20 out to radii $\sim 1'$ due to scattering in the interstellar medium.

Subject headings: astrometry — pulsars: individual (SGR 1806−20) — stars: neutron — X-rays: stars

1. INTRODUCTION

The soft γ-ray repeaters (SGRs; see Hurley 2000 for a recent observational review) are enigmatic sources that were discovered through their repeated bursts of hard X-rays/soft γ rays. With the improvement in imaging afforded by the current generation of X-ray satellites, SGRs were found to emit softer quiescent X-rays as well. They are generally thought to be young ($< 10^4$ yr) neutron stars with extremely strong magnetic fields, or magnetars (see, e.g., Duncan & Thompson 1992; Thompson & Duncan 1993). This belief has been motivated by their associations with young supernova remnants (SNRs; Evans et al. 1980; Kulkarni & Frail 1993; Vasisht et al. 1994) and sites of massive star formation (Fuchs et al. 1999; Vrba et al. 2000), the energetics of their bursts (Paczyński 1992; Thompson & Duncan 1995), and the detection of X-ray pulsations with long (5–10 s) periods and high ($\sim 10^{-11}$ s s^{-1}) spin-down rates (see, e.g., Kouveliotou et al. 1999).

The proposed identification of an SNR, the plerion G10.0−0.3, with SGR 1806−20 by Kulkarni & Frail (1993) played a key role in establishing the connection of SGRs with SNRs and thence with young stars. This identification renewed confidence in the association of N49 with the 1979 March 5 event (SGR 0526−66) and motivated SNR associations for two of the remaining SGRs, SGR 1900+14 (Vasisht et al. 1994) and SGR 1627 41 (Hurley et al. 1999b). The association of SGR 1806−20 with G10.0−0.3 was strengthened by the discoveries of a nonthermal core in G10.0−0.3 (Kulkarni et al. 1994; Vasisht, Frail, & Kulkarni 1995) that changed on month-to-year timescales and of a nearby luminous blue variable star (LBV; Kulkarni et al. 1995; van Kerkwijk et al. 1995). It was proposed that all these sources were related, with the LBV as either a current or past binary companion to SGR 1806−20 (van Kerkwijk et al. 1995) and the variable radio source the result of episodic mass loss from SGR 1806−20 (Frail, Vasisht, & Kulkarni 1997).

However, a recent moderate-precision IPN position (Hurley et al. 1999a) placed SGR 1806−20 outside the nonthermal core suggested by Kulkarni et al. (1994) to be the seat of the SGR. Furthermore, the association of SGR 1900+14 with SNR G42.8+0.6 was questioned (Lorimer & Xilouris 2000). In summary, the entire issue of whether SGRs are associated with SNRs is now open to debate (see review by Gaensler et al. 2001).

The purpose of this paper is to provide an independent localization of the quiescent X-ray counterpart of SGR 1806−20. SNR–SGR associations are useful for establishing independent ages for SGRs, the nonthermal core of G10.0−0.3 provides key energetics constraints, and the LBV star hints at a binary origin and evolutionary scenario for SGR 1806−20. Determining whether or not these associations are true is therefore key to assessing the nature of SGR 1806−20.

2. OBSERVATIONS AND ANALYSIS

We observed SGR 1806−20 with the *Chandra X-Ray Observatory* on two occasions, beginning on 2000 July 24.7 UT and 2000 August 15.7 UT, with durations of 4.9 ks and 31 ks, respectively (see Table 1). Both observations were taken with the aim point on the backside-illuminated ACIS-S3 detector. The first observation was taken in the standard full-frame CCD mode, with 3.24 s time resolution, while the second observation was acquired in a $\frac{1}{4}$ subarray mode that provides increased time resolution of 0.81 s, but with a reduced field of view ($\frac{1}{4}$ of the full-frame area). All the data suffer from the effects of photon pileup: $\approx 50\%$ of the data from the first observation

TABLE 1

SUMMARY OF *Chandra* OBSERVATIONS

Date	MJD of Start	Exposure (ks)	ACIS-S3 Counts[a]	TE Mode
2000 Jul 24	51749.7	4.9	833	Normal
2000 Aug 15...	51771.8	31.1	7738	$\frac{1}{4}$ subarray

[a] Accepted counts (standard processing) within $3''.3 = 10\,\sigma$ radius.

and $\lesssim 10\%$ of the data from the second are corrupted. Pileup occurs when "two or more photons are detected as a single event."[1] This results in three main effects: (1) the detected event has an energy that is the sum of all the incident photon energies; (2) the count rate is diminished; and (3) the grades of the incoming photons will be altered, so that some may be cataloged as "cosmic rays" or other undesirable events and will therefore be rejected. The consequences of these effects on an observation of a bright source, in addition to modification of the spectrum, are that the spatial profile is altered, because the diminishment of the count rate is worst for the pixels at the center of the point-spread function (PSF), and that some regions with especially high rates of incoming photons may seem devoid of all events, because the total amplitude of the detected events exceeds the onboard energy threshold and is rejected (similar to grade migration).

Because of pileup, especially effects 1 and 2 above, we cannot perform spectroscopy with great accuracy, and we defer such analysis until tools for correcting pileup become publicly available. As noted, pileup will also affect the spatial profile of the source (it depresses the center of the PSF relative to the wings) and the timing (two photons arriving together will be counted as one), but the analysis presented here should not be affected significantly, because we are not interested in the detailed shape of the PSF within $1''$ or in the exact light curve—overall, the position and period will be preserved.

We examined the two images and found a single bright source near the expected location of the SGR. This source is consistent with an unresolved point source (Gaussian $\sigma = 0''.33$; Marshall et al. 2001). In order to determine if this source is indeed the SGR, we searched for the expected 7 s pulsations (Kouveliotou et al. 1998). We first barycentered the data using the AXBARY software. The 5 ks observation had too few photons to detect anything, and it was taken with 3.24 s time resolution. The 31 ks data had sufficient photons and was taken in the $\frac{1}{4}$ subarray mode, which gives 0.81 s sampling. We therefore added a random number $\sim \mathcal{U}(0, 0.81)$ to the time-of-arrival values to eliminate any effects of sampling. We then performed a Z_1^2 test (de Jager, Swanepoel, & Raubenheimer 1989) on the 31 ks data and found a very significant periodicity at $P \approx 7.5$ s. To refine this measurement, we performed a phase connection of the *Chandra* data in the manner of Fox et al. (2001). We connected four segments of ≈ 8000 s, each of which had been binned to 1 s resolution (appropriate for the 0.8 s sampling). We find, referenced to MJD 51772.0 (TDB), a phase of 0.12(5) cycles, a period $P = 7.4925(2)$ s, and a period derivative $|\dot{P}| < 4 \times 10^{-8}$ s s^{-1} at 90% confidence. The pulsations have a sinusoidal profile and an rms pulsed fraction of $\approx 7.4\%$—a folded pulse profile is shown in Figure 1.

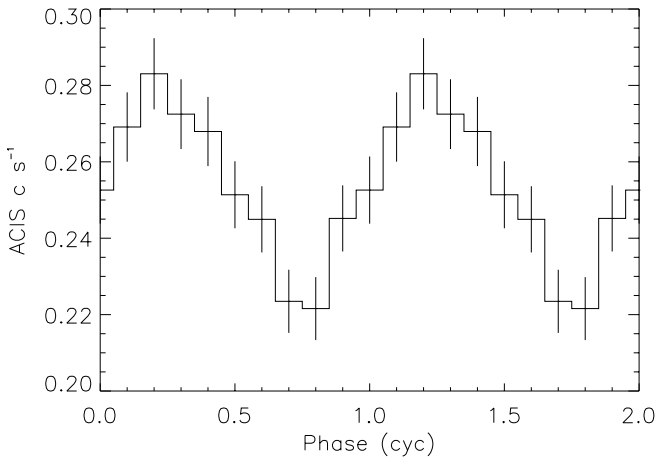

FIG. 1.—Pulse profile for SGR 1806−20 from the 31 ks observation, folded at the best period of 7.4925 s. The profile is shown over two periods for clarity. No corrections for pileup have been made.

Although the count rate and spectrum from our observations are uncertain because of pileup, we can roughly estimate the source flux through use of previously published spectra for SGR 1806−20 (Mereghetti et al. 2000). With the count rate from the 31 ks observation (the least corrupted), we see 0.5–10 keV fluxes of $\approx 7 \times 10^{-12}$ ergs s^{-1} cm^{-2} (absorbed) and $\approx 2 \times 10^{-11}$ ergs s^{-1} cm^{-2} (unabsorbed). These values are entirely compatible with the 2–10 keV fluxes found by Mereghetti et al. (2000). The observed count rates are constant throughout the observations.

Given the 0.81 s sampling and the presence of pileup, it is not surprising that we do not see any significant bursts of the type typically seen during observations of SGRs (see, e.g., Fox et al. 2001). We note that it is likely that any bursts during this observation were probably not recorded because of pileup and onboard/postprocessing rejection of anomalous events.

2.1. *Localization*

To accurately localize SGR 1806−20, we measured its position in both *Chandra* data sets. The measured positions from the two observations are consistent to $0''.04$, suggesting that the stochastic position errors are minimal. There may, however, be systematic errors on the order of $1''$ due to overall uncertainties in the *Chandra* aspect solutions.

To correct for such errors, we searched the *Chandra* images for background sources to use as position references. We found seven weak sources in the 5 ks image. None had a match in the SIMBAD database, but two sources (detected at 2.5 σ confidence) were coincident with stars. In the 31 ks image we found 11 sources, two of which had matches in the USNO-A2.0 catalog: one detected at 4 σ confidence that was also in the 5 ks image, the other detected at 2.5 σ confidence. We summarize the X-ray–detected USNO stars in Table 2. There are ≈ 4.3 USNO stars arcmin^{-2} in this region, giving chance coincidence rates of $\sim 0.1\%$ between an individual X-ray source and a USNO star, supporting our identifications. We are pursuing photometric and spectroscopic observations of these stars that should allow us to classify them and to verify these identifications (see, e.g., van den Berg & Verbunt 2001).

[1] See http://asc.harvard.edu/udocs/docs/POG/MPOG/node11.html#SECTION04616000000000000000.

TABLE 2

USNO STARS DETECTED IN *Chandra* IMAGES

Star	X-Ray Position		σ[b] (arcsec)	USNO Position[a]		Δr (arcsec)
	α_{2000}	δ_{2000}		α_{2000}	δ_{2000}	
Sources in 5 ks image:						
A.....	18 08 24.93	−20 24 33.2	0.2	18 08 24.95	−20 24 32.6	0.7
B.....	18 08 43.41	−20 23 58.8	0.3	18 08 43.46	−20 23 58.1	1.0
Sources in 31 ks image:						
B.....	18 08 43.43	−20 23 58.6	0.1	18 08 43.46	−20 23 58.1	0.6
C.....	18 08 41.43	−20 25 12.8	0.3	18 08 41.47	−20 25 12.6	0.6

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Uncertainties on USNO positions are assumed to be 0.″2 rms in each coordinate.

[b] rms uncertainty in each coordinate.

Using the USNO stars to derive offsets for the astrometry, we find corrections of $\Delta\alpha = 0.''4$ and $\Delta\delta = 0.''5$, consistent between both *Chandra* images and comparable in magnitude to the expected aspect uncertainties.[2] We find a corrected position for SGR 1806−20 of $\alpha_{2000} = 18^h08^m39^s.32$ and $\delta_{2000} = -20°24'39''.5$. This position has rms uncertainties of 0.″3 in each coordinate (from centroiding the X-ray sources and intrinsic USNO uncertainties of 0.″2; Deutsch 1999) but should be free from systematic uncertainties.

This position agrees very well (within the 1 σ error ellipse) with the position determined from IPN measurements (Hurley et al. 1999a), and is $14'' \pm 0.''5$ from the position of the nonthermal nebula from Frail et al. (1997); see Figure 2.

2.2. *Extended Emission*

X-rays are scattered by dust grains in the interstellar medium, and one expects to see halos of size 0.′1–100′ toward objects with hydrogen column density of 10^{21} cm^{-2} or greater (see, e.g., Overbeck 1965; Predehl & Schmitt 1995). This issue was first discussed by Overbeck (1965), and the *Einstein Observatory* found the first such halos (Rolf 1983; Catura 1983). The most comprehensive work to date has been carried out by Predehl and associates using *ROSAT* (Predehl & Schmitt 1995).

The recent interest in scattering halos around SGRs has been motivated by the discovery of such a halo around SGR 1900+14 (Kouveliotou et al. 2001). As with SGR 1900+14, one expects an X-ray halo around SGR 1806−20 from scattering off dust. We therefore examined the radial profile of SGR 1806−20 from the 31 ks observation for better signal-to-noise ratio. In Figure 3, we show the radial profile of SGR 1806−20 from this observation, along with the profile from a MARX[3] simulation (using the spectrum for SGR 1806−20 from Mereghetti et al. 2000) scaled to the same normalization for the inner portion (see Kouveliotou et al. 2001); such simulations should be accurate out to radii of a few arcminutes.[4] The background was measured from the ACIS-S3 chip far (>3′) from SGR 1806−20 and includes both instrumental and unresolved source contributions. We corrected the background estimate to $r \lesssim 1'$ with a MARX simulation of the ACIS-S3 response to account for vignetting and other effects. We find the variation in radial response to be small for $r \lesssim 1'$ and therefore show a constant background in Figure 3. One sees very good agreement between the data and the model at small radii, showing that pileup has not substantially corrupted the radial profile of this observation (the model did not incorporate pileup, because MARX does not correctly simulate the back-illuminated CCDs). But there is a clear deviation from the model PSF at large radii ($\gtrsim 3''$) that we believe to

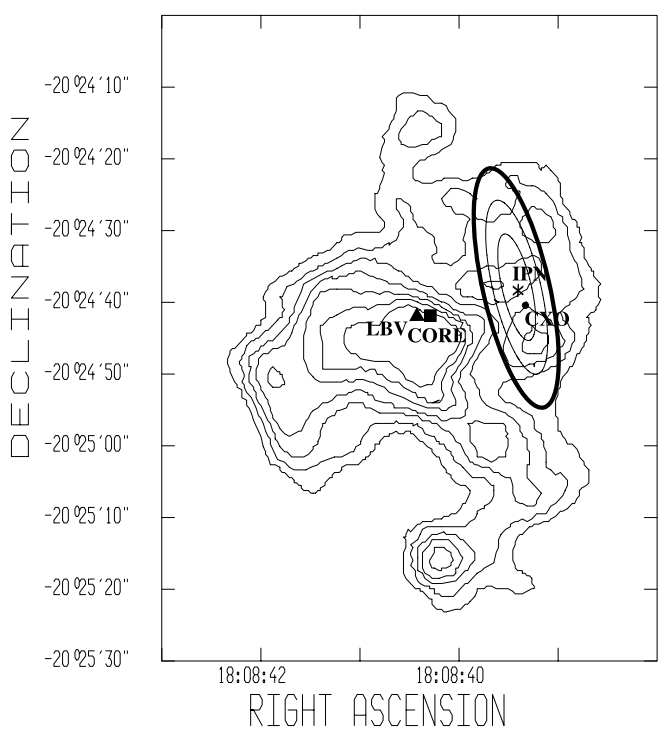

FIG. 2.—VLA image (3.6 cm) of central portion of G10.0−0.3 (Frail et al. 1997), with position of radio core at square labeled "CORE." Superimposed are 1, 2, and 3 σ annuli around the best-fit IPN position (*asterisk labeled* "IPN") from Hurley et al. (1999a), the corrected *Chandra* position (*circle labeled* "CXO"), and the position of the LBV star (*triangle labeled* "LBV"; Kulkarni et al. 1995). Note that the position of the core indicated in Hurley et al. (1999a) is slightly incorrect (K. Hurley 2001, private communication).

[2] See http://asc.harvard.edu/mta/ASPECT/celmon.

[3] See http://space.mit.edu/ASC/MARX.

[4] See http://asc.harvard.edu/cal/Hrma/hrma/psf/psfwings/psfwings.html.

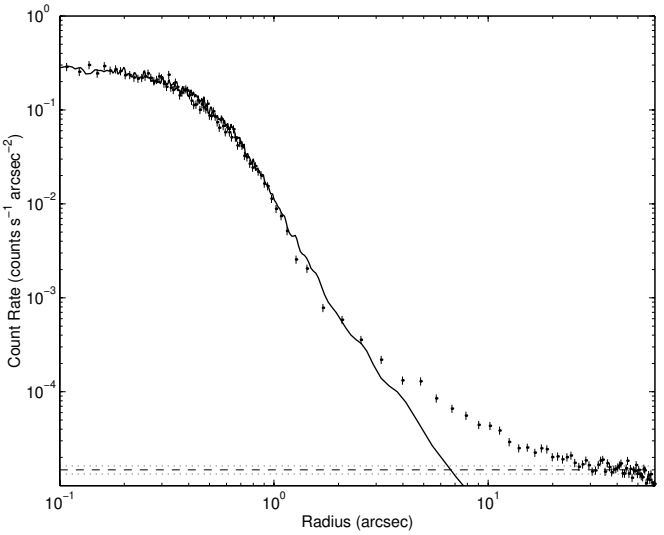

FIG. 3.—Radial profile of SGR 1806−20 from the 31 ks observation (*points*), along with that of a MARX model of the *Chandra* PSF (*solid line*), scaled to the same normalization for $r \lesssim 1''$. The mean background level (corrected for vignetting) is shown by the dashed line, with $\pm 1\ \sigma$ levels indicated by the dotted lines.

be indicative of a dust halo contributing $\sim 0.5\%$ to the total X-ray flux. To verify this interpretation, we examined the radial profile as a function of the phase of SGR 1806−20. The profile for the portion of the period when SGR 1806−20 is "on" has of course more counts at small radii than the profile when SGR 1806−20 is "off." However, the outer portion ($r \gtrsim 3''$) that we identify as the halo is identical between "on" and "off," indicating that the pulsations of SGR 1806−20 are smeared out in the halo. This suggests that the extended emission is not an instrumental property, because scattering wings or something similar would scale with the immediate flux of the source instead of averaging over time, as observed here. We note, though, that while the data do show a slight softening toward higher radii (as expected from the E^{-2} dependence of the scattering cross section; see, e.g., Predehl et al. 2000), we cannot determine in detail how the halo profile changes with energy. This could be due to the relatively hard spectrum of SGR 1806−20, so that the cross section does not vary much over the energy range for which there are significant counts (2–6 keV). It could also be an effect of poor statistics, where a longer observation would show an energy-dependent halo. Regardless, we must caution the reader as to this interpretation of the extended emission.

3. DISCUSSION

The X-ray position of SGR 1806−20 is now without doubt incompatible with the positions of both the nonthermal core of G10.0−0.3 and the LBV star, although those two positions still agree to 1″. We therefore follow Hurley et al. (1999a) and Gaensler et al. (2001) in suggesting that the LBV, not SGR 1806−20, powers the core of G10.0−0.3. As outlined in Hurley et al. (1999a), the LBV can easily explain the energetics and changing morphology of the nonthermal core. SGR 1806−20 could still be associated with G10.0−0.3 as a whole, although this is unlikely, given the proximity of the core and the LBV to the center of G10.0−0.3.

However, we still have a remarkable coincidence: within a circle $\approx 10''$ in radius (0.7 pc at 14.5 kpc distance; Corbel et al. 1997), we have an SGR (SGR 1806−20), an LBV, and a massive star cluster (Fuchs et al. 1999). All three of these objects are exceedingly rare. In addition, there is an SNR[5] at the same position. While it is hard to draw quantitative conclusions from this coincidence, because none of the objects involved have well-defined populations and this region of the sky has been studied in great depth, it is still noteworthy. Individual distances to these sources are not known, but it is plausible that they are all 14.5 kpc away (Corbel et al. 1997; Fuchs et al. 1999). We believe that, even if SGR 1806−20 is not directly associated with the LBV or G10.0−0.3, it was likely born in the same cluster, which requires that the progenitor of SGR 1806−20 have been quite massive, to have had a supernova before the LBV or the stars in the cluster (as noted by Hurley et al. 1999a). Perhaps this is a case of an extremely high mass star ($\gtrsim 50\ M_{\odot}$) forming a neutron star as a result of large mass loss over its lifetime (Fryer & Kalogera 2001). Alternatively, the sources could all have originated in the same molecular cloud, but the supernova from SGR 1806−20 could have triggered the star formation that led to the LBV and the cluster.

The angular scale where the scattering halo departs from the PSF is smaller than that seen for *ROSAT* data, and we do not measure the halo out to such large radii, so the relations presented for *ROSAT* data by Predehl & Schmitt (1995) are not directly applicable. However, we can correct the relation between fractional halo intensity and hydrogen column density from Predehl & Schmitt (1995) to the appropriate energy and angular scale range for our data, and we find an expected halo intensity of $\approx 0.3\%$ based on $N_{\rm H} = 6 \times 10^{22}$ cm^{-2}, as determined by Mereghetti et al. (2000). This is very similar to the measured intensity, supporting the conclusion that we see a halo, not an instrumental artifact, and implying that the size distribution of the scattering grains at small angular scales is similar to that seen for the larger *ROSAT* halos.

The halo we see is very similar (in angular scale and fractional intensity) to that seen for SGR 1900+14 (Kouveliotou et al. 2001), suggesting that they lie behind similar dust columns (or possibly that both "halos" are in fact instrumental effects). As with SGR 1900+14, the pulsations of SGR 1806−20 are too smeared out in the halo to use them to determine a geometric distance (see Trümper & Schönfelder 1973; Predehl et al. 2000). However, if observations were made of SGR 1806−20 soon ($\sim$ hours to days) after a significant change in the level of its emission (e.g., following a giant flare), such that the change was visible in the halo, a distance determination could be made. *BeppoSAX* is probably the only current satellite that has the necessary slew capabilities coupled with spatial resolution and soft-energy response to perform these observations.

The measured period of SGR 1806−20 is not consistent with either its long-term spin-down (Woods et al. 2000; Mereghetti et al. 2000) or the newer spin-down measured from phase-connected *RXTE* observations (Woods et al. 2000), as seen in Figure 4. While SGR 1806−20 exhibits

[5] Although Gaensler et al. (2001) have argued that G10.0−0.3 is not an SNR.

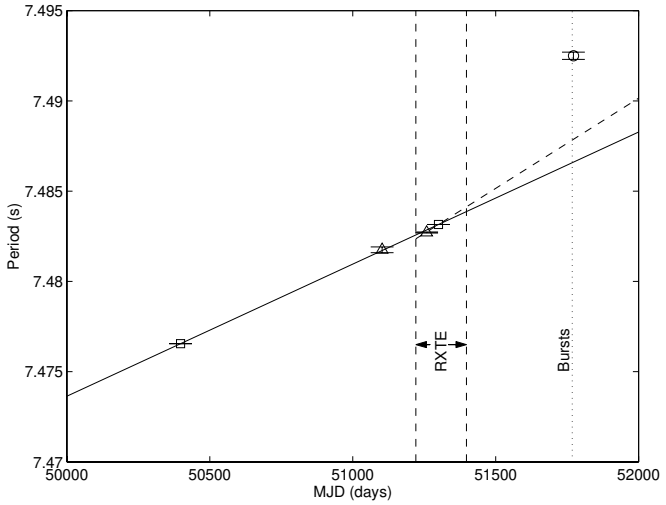

FIG. 4.—Period evolution of SGR 1806−20, from *RXTE* (*squares*; Woods et al. 2000), *BeppoSAX* (*triangles*; Mereghetti et al. 2000), and *Chandra* (*circle*; this work). The solid line is a linear least-squares fit to the *RXTE* and *BeppoSAX* data with $\dot{P} = 8.469(1) \times 10^{-11}$ s s^{-1}, from which the *Chandra* data deviate significantly. Dashed vertical lines labeled "RXTE" delimit the phase-connected *RXTE* ephemeris (Woods et al. 2000), which we then extrapolate as the diagonal dashed line. Dotted vertical line marked "Bursts" indicates the time of the burst activity that preceded the *Chandra* observation (Göğüş et al. 2000).

substantial timing noise (Woods et al. 2000), the long-term trend was generally stable for a number of years. However, Woods et al. (2000) found that at a single epoch the instantaneous spin-down rate for SGR 1806−20 was higher by a factor of 1.5 than the global trend, and to account for the new *Chandra* data, the spin-down rate must have increased even more. Between the last *RXTE* measurement from Woods et al. (2000) and our measurement, the average spin-down rate is $2.3(1) \times 10^{-10}$ s s^{-1}, which is a factor of 2 higher than the largest $\dot{P}$ previously measured for this source. This change is similar to the large change in both spin period and spin-down rate seen for SGR 1900+14, following its activation during 1998 August (Marsden, Rothschild, & Lingenfelter 1999; Woods et al. 1999), and for the anomalous X-ray pulsar 1E 1048.1−5937 (Kaspi et al. 2001). SGR 1806−20 must have either increased its long-term spin-down substantially or undergone a momentary large change in spin-down. Such sudden changes in spin-down are capable of being produced within the magnetar framework (Thompson et al. 2000), either by particle outflows or by realignment of the neutron star crust, but they are typically assumed to be episodic and triggered by bursting or flaring activity (Woods et al. 1999; Thompson et al. 2000). We note that Göğüş et al. (2000) did observe a period of moderate burst activity for SGR 1806−20 several days before the 31 ks *Chandra* observation, but this was too close to the *Chandra* observation to have affected the spin period significantly. Whether sudden or gradual, the change in rotation for SGR 1806−20 had to start before the bursts observed by Göğüş et al. (2000) (unless the spin-down is orders of magnitude larger than previously seen), so these changes were not caused by burst activity. This suggests that the more gradual change is the correct mechanism in this case, perhaps because of continuing plastic deformation of the crust (see, e.g., Thompson et al. 2000). In addition, spin-down cannot be used to determine the ages or magnetic fields of any SGR in the manner typical for radio pulsars (see, e.g., Manchester & Taylor 1977), as noted by Thompson et al. (2000). We must instead rely upon arguments relating to the super-Eddington bursts (Thompson & Duncan 1995), global energetics, and similar phenomena as indicators of the magnetar-like fields of these objects.

4. CONCLUSIONS

We have confirmed the position of Hurley et al. (1999a) for SGR 1806−20 and determined that it is near neither the nonthermal core of G10.0−0.3 (Frail et al. 1997) nor the luminous blue variable star (van Kerkwijk et al. 1995), although those two sources may be associated. Through comparison of the radial profile of SGR 1806−20 with a model PSF, we see evidence of a broad X-ray–scattering halo. Given its violent nature, SGR 1806−20 may produce changes in its X-ray emission such that observations of this halo could lead to a geometric distance determination, thereby fixing the luminosity scale of SGRs and locating SGR 1806−20 in three dimensions relative to the massive star cluster (Fuchs et al. 1999), the LBV, and other nearby objects.

Timing analysis of the *Chandra* data shows that SGR 1806−20 is not continuing the long-term trend of spin-down that it has followed for the past 4 yr. This is similar to changes in spin-down observed for SGR 1900+14 following the 1998 August outbursts, although only minor bursts were observed for SGR 1806−20 around the time of these observations, and these bursts are unlikely to have been responsible for the deviation from normal spin-down.

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