CHANDRA ASTROMETRY SETS A TIGHT UPPER LIMIT TO THE PROPER MOTION OF SGR 1900+14

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ABSTRACT

The soft gamma-ray repeater SGR 1900+14 lies a few arcminutes outside the edge of the shell supernova remnant (SNR) G42.8+0.6. A physical association between the two systems has been proposed—for this and other SGR–SNR pairs—based on the expectation of high space velocities for SGRs in the framework of the magnetar model. The large angular separation between the SGR and the SNR center, coupled with the young age of the system, suggests a test of the association with a proper motion measurement. We used a set of three *Chandra*/Advanced CCD Imaging Spectrometer observations of the field spanning approximately five years to perform accurate relative astrometry in order to measure the possible angular displacement of the SGR as a function of time. Our investigation sets a 3σ upper limit of 70 mas yr^{-1} to the overall proper motion of the SGR. Such a value argues against an association of SGR 1900+14 with G42.8+0.6 and adds further support to the mounting evidence of an origin of the SGR within a nearby compact cluster of massive stars.

Key words: ISM: individual (G42.8+0.6) – stars: neutron – supernova remnants – X-rays: individual (SGR 1900+14) – X-rays: stars

1. INTRODUCTION

Soft gamma-ray repeaters (SGRs; see, e.g., Hurley 2000; Woods & Thompson 2006; Mereghetti 2008, for reviews) are a handful of four (plus a few candidates) sources of short bursts of soft gamma rays. SGRs were originally thought to be a peculiar subclass of gamma-ray bursts (GRBs). In contrast to the behavior of classical GRBs, SGRs produce series of bursts over various timescales and the events are characterized by a soft spectral shape. SGRs have a very rich high-energy phenomenology. Apart from the flaring activity, characterized by the emission of multiple, short (~ 0.1 s) bursts with peak luminosities of $\sim 10^{41}$ erg s^{-1}, sometimes culminating in dramatic, very energetic *giant flares* with peak luminosity exceeding 10^{47} erg s^{-1} (as was the case of the 2004 December 27 event from SGR 1806–20; Hurley et al. 2005), SGRs display persistent emission from 0.1 to hundreds of keV, with pulsations in the 5–8 s range, and with significant variability in the flux, spectral shape, pulse shape, and pulsed fraction; they also exhibit glitches and an irregular period derivative.

This phenomenology has been interpreted within the framework of the *magnetar* model. SGRs are believed to be young, isolated neutron stars (INSs) endowed with an ultrahigh magnetic field ($B \sim 10^{15}$ G), which is thought to be the energy reservoir for all high-energy emissions (Duncan & Thompson 1992; Thompson & Duncan 1995, 1996). It is now commonly accepted that Anomalous X-ray Pulsars (AXPs), a peculiar class of X-ray pulsars (see Woods & Thompson 2006; Mereghetti 2008, for reviews), could also be magnetars, in view of a close similarity of several aspects of the high-energy phenomenology.

The identification of SGRs with young INSs is on a rather firm basis. However, in the past, an important supporting argument has been their possible association with supernova remnants (SNRs). This provided a link between SGR formation and supernova explosions, and also set an upper limit to their age, in view of the short lives of SNRs. Indeed, a possible SNR

association had been claimed for all SGRs (Hurley 2000). The validity of this association was later reconsidered as new multiwavelength observations became available (see Gaensler et al. 2001, and references therein). In one case (SGR 1806–20), the mere existence of a nearby SNR was ruled out. For the remaining cases, the SGR positions, close to the edges or even outside their SNRs, cast doubt on the associations, based on two main considerations: (i) the significant chance alignment probability and (ii) the need for large spatial velocities (well in excess of 1000 km s^{-1}). Although such large velocities are not unheard of in the neutron star family (Hobbs et al. 2005), AXPs do not show any evidence of them. This would suggest that AXPs and SGRs are different classes of INSs, originating in intrinsically different supernova explosion processes, in contrast to the robust evidence of a very close relationship between SGR and AXP families. In view of this, all SGR–SNR associations have been reconsidered, and a possible association of two SGRs with nearby, massive star clusters has been proposed (SGR 1806–20 by Fuchs et al. 1999; SGR 1900+14 by Vrba et al. 2000).

2. SGR 1900+14 AND SNR G42.8+0.6

SGR 1900+14 lies outside the rim of G42.8+0.6, a shell-type, $\sim 10^4$ year old radio SNR located at a distance of 3–9 kpc (Marsden et al. 2001). An association between the two systems was originally proposed by Vasisht et al. (1994) and Hurley et al. (1996). SGR 1900+14 lies toward a rather complicated region of the Galaxy, and Gaensler et al. (2001) estimated a chance probability for the alignment of an SNR to be as high as 4%. Kaplan (2002) even increased this estimate to $\sim 23\%$. Lorimer & Xilouris (2000) detected a young ($\tau_c \sim 38$ kyr) radio pulsar about 2 arcmin away from the SGR. Such a pulsar could also be plausibly associated with G42.8+0.6. Moreover, Vrba et al. (2000) discovered a massive star cluster very close (~ 12 arcsec) to the position of the SGR. Such observations weakened the case of an association between SGR 1900+14

Table 1
Chandra Observations of the Field of SGR 1900+14

Date	MJD	Obs. ID	Instrument	Exposure Time
2001 Jun 17	52,077	1954	ACIS/I	30.1 ks
2002 Mar 11	52,344	3449	ACIS/S	2.7 ks
2006 Jun 4	53,890	6731	ACIS/I	25.0 ks

Note. All observations were performed using the timed exposure mode and the faint event telemetry format.

and G42.8+0.6. Very recently, Wachter et al. (2008) discovered an infrared ring surrounding SGR 1900+14 with *Spitzer*. This structure was interpreted as the rim of a dust cavity produced by past giant flares from the SGR, heated by a nearby star cluster. This would point to a possible association of SGR 1900+14 with the star cluster, although a large difference in reddening toward the SGR and the cluster remains to be explained

In this work, we directly probe the association of SGR 1900+14 with SNR G42.8+0.6 through a proper motion measurement. Such a possibility had been suggested by Hurley et al. (2002). The angular separation between the SGR and the center of the SNR is ~ 18 arcmin (Hurley et al. 2002). Adopting a value of 10^4 yr as a conservative estimate for the age of the system (Thompson et al. 2000), the SGR–SNR association would require a proper motion of at least 0.11 arcsec yr^{-1}. Such a proper motion can be measured using multi-epoch observations with the *Chandra X-Ray Observatory*. The superb angular resolution of its optics and the stability of aspect reconstruction with its imaging detectors allow measurements of tiny angular displacements through accurate relative astrometry (see, e.g., Motch et al. 2007, 2008).

3. *CHANDRA* OBSERVATIONS AND DATA ANALYSIS

SGR 1900+14 has been observed three times by *Chandra* between 2001 and 2006 using the Advanced CCD Imaging Spectrometer (ACIS). The first observation was carried out in response to an AO-2 proposal whose goal was to obtain a baseline measurement for proper motion studies. A log of the available data is given in Table 1. We retrieved event files from the *Chandra* X-Ray Center Data Archive. All the data sets have gone through "reprocessing III"[6] with updated software and calibration. According to the *Chandra* X-Ray Center guidelines,[7] no further reprocessing is required and archival "level 2" data were adopted as a starting point. We used the *Chandra* Interactive Analysis of Observation software (CIAO version 3.3) for our analysis.

No significant background flares affected the observations. We removed pixel randomization (we checked a posteriori that fully consistent results are obtained by using standard pixel position randomization) and generated images of the field by selecting photons in the 0.3–8 keV energy range, binning the CCD pixel size by a factor of 2. The target was imaged close to the aimpoint on the ACIS/I3 detector for Observations 1 and 3 and on the ACIS/S3 detector for Observation 2.

Source detection was done using the WAVDETECT task, with wavelet scales ranging from 1 to 16 pixels, spaced by a factor of $\sqrt{2}$. A detection threshold of 10^{-5} was selected in order to avoid missing faint sources. Cross-correlation of the source lists produced for each observation (adopting a maximum source

distance of 3 arcsec) allowed us to reject spurious detections (about ~ 70 per field in Observations 1 and 3). We identified a set of 31 common sources in Observations 1 and 3 (excluding the target), while only six such sources were found in Observation 2, which was significantly shorter and had a smaller field of view (FOV).

The probability of a chance alignment of two false detections is estimated to be of order $\leqslant 0.1\%$. Thus, we may safely assume that all of the selected common sources are real.

The uncertainty affecting the source's positions in the reference frame of each image depends on the source signal to noise as well as on the distance from the aimpoint (because of the point-spread function (PSF) degradation as a function of the off-axis angle). The position of the target, the brightest source in the field, located close to the aimpoint, was determined with a 1σ error of 0.02 pixels per coordinate, while the position of a typical faint source located several arcmin off-axis is affected by an uncertainty of order 1 pixel per coordinate.

4. RELATIVE ASTROMETRY

Relative astrometry relies on accurate image superposition, based on a grid of good reference sources. The positions of the sources selected in Section 3, together with their uncertainties, were used to compute the best transformation needed to superimpose our multi-epoch images. We took Observation 3 as a reference. To register the frames, we used a simple rotation and translation. We found a strong dependence of the residuals on the positions of the reference sources as a function of the distance to the aimpoint. Superimposing Observation 1 on Observation 3, these residuals are of order 0.2 pixels per coordinate within 4 arcmin from the aimpoint (12 reference sources); residuals grow to ~ 0.6 pixels per coordinate between 4 and 6 arcmin off-axis (8 reference sources); using 10 sources at off-axis distances larger than 6 arcmin, the residuals are of order 1.3 pixels per coordinate. This is most likely due to the degradation of the PSF with the off-axis angle, which hampers an accurate localization of the sources.

We decided to use only the inner portion of the field (we checked a posteriori that no different astrometric solutions are obtained using the entire sample of reference sources). After excluding a source deviating at more than 3σ with respect to the rms, we obtained a very good superposition using 11 sources, yielding a 1σ error on the frame registration as small as 50 mas per coordinate. The residuals of the reference source positions are ~ 100 mas per coordinate. To be conservative, this value was assumed as the 1σ uncertainty affecting our frame registration. We note that the best-fit roto-translation implies a frame registration with a similar uncertainty (i.e., no significant transformation is required). We repeated the same exercise to superimpose Observation 2 on Observation 3, which yielded similar, consistent results, although based on a smaller sample of reference sources. We then computed the target position in the reference frame of Observation 3, in order to evaluate its possible displacement over the ~ 5 year interval spanned by the observations.

We found no significant displacement in either coordinate. Accounting for the uncertainty in the target position in each image, as well as for the uncertainty involved in the frame superposition, a linear fit to the observed relative positions sets an upper limit to the proper motion of SGR 1900+14 of 17 mas yr^{-1} per coordinate. The 3σ upper limit to the overall proper motion of the source in the plane of the sky is 70 mas yr^{-1}.

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[6] See http://cxc.harvard.edu/ciao/repro_iii.html.
[7] See http://cxc.harvard.edu/ciao/threads/createL2/.

Table 2
Multi-epoch Absolute Positions (J2000) of SGR 1900+14

R.A. (error)	Decl. (error)	Date	Instrument
$19^h07^m14\overset{s}{.}33$ ($0\overset{s}{.}15$)	$+09°19'20\overset{''}{.}1$ ($0\overset{''}{.}15$)	1998 Sep 10	VLA
$19^h07^m14\overset{s}{.}33$ ($0\overset{s}{.}21$)	$+09°19'19\overset{''}{.}6$ ($0\overset{''}{.}21$)	2001 Jun 17	ACIS/I
$19^h07^m14\overset{s}{.}33$ ($0\overset{s}{.}31$)	$+09°19'19\overset{''}{.}8$ ($0\overset{''}{.}31$)	2002 Mar 11	ACIS/S
$19^h07^m14\overset{s}{.}31$ ($0\overset{s}{.}21$)	$+09°19'19\overset{''}{.}8$ ($0\overset{''}{.}21$)	2006 Jun 4	ACIS/I

Note. Errors are at a 68% confidence level.

5. ABSOLUTE ASTROMETRY: X-RAY VERSUS RADIO POSITIONS

A precise localization of SGR 1900+14 was obtained on 1998 September 10, thanks to Very Large Array (VLA) observations of the source after the giant flare of August 27 (Hurley et al. 1999). The accurate radio position was R.A. = $19^h07^m14\overset{s}{.}33$, decl. = $+09°19'20\overset{''}{.}1$ (J2000) with a 1σ uncertainty of $0\overset{''}{.}15$ per coordinate (Frail et al. 1999). We will take advantage of *Chandra* accurate absolute astrometry to compare the X-ray position of the target with the 1998 radio position.

Chandra absolute localization accuracy for on-axis sources has been carefully evaluated by the calibration team. A typical radial uncertainty of $\sim 0\overset{''}{.}4$ at a 68% confidence level affects ACIS/I positions,[8] while for ACIS/S observations, this uncertainty is $\sim 0\overset{''}{.}2$. In order to assess (and possibly improve) the absolute astrometry of the *Chandra* data set on SGR 1900+14, we have cross-correlated the "good" source list obtained in Section 3 with sources in the Two-Micron All-Sky Survey (2MASS; Skrutskie et al. 2006) catalog, which has an astrometric accuracy of order $0\overset{''}{.}1$.[9]

For Observations 1 and 2, we found five coincidences in 2MASS within $0\overset{''}{.}8$ of the X-ray position. Increasing the correlation radius up to $2\overset{''}{.}7$ yields no further match. This suggests that the five 2MASS sources are very likely to be the infrared counterparts of the corresponding X-ray sources. Infrared colors and the X-ray-to-infrared flux ratio suggest such sources to be late stars of K–M spectral class. We used the five source positions to register the *Chandra* images on the accurate 2MASS reference frame by fitting a roto-translation, which yielded an rms of ~ 200 mas per coordinate. We note that the *Chandra*–2MASS superposition did not require a significant transformation (i.e., the corrections are of the same order of the residuals). We repeated the same operation using Observation 3, where two of the above sources were found and were used to adjust the astrometry by fitting a simple translation, with an rms residual of ~ 300 mas per coordinate. We computed the overall uncertainty in the absolute position of SGR 1900+14 by summing the target localization accuracy on *Chandra* images, the rms of the *Chandra*–2MASS frame superposition, and the 2MASS absolute astrometric accuracy, in quadrature.

The resulting positions of the target are given in Table 2. These positions are (as expected) fully consistent with the accurate radio one computed in 1998. With a simple linear fit, we estimate that absolute astrometry sets a 3σ upper limit to the proper motion of SGR 1900+14 of 100 mas yr^{-1} per coordinate. Although such a limit is slightly less stringent than that obtained through relative astrometry, this is an important consistency check of our result.

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[8] See http://cxc.harvard.edu/cal/ASPECT/celmon/.
[9] See http://spider.ipac.caltech.edu/staff/hlm/2mass/overv/overv.html.

6. CONCLUSIONS

Relative astrometry using a set of three *Chandra* observations spanning five years yields no evidence of any angular displacement of SGR 1900+14 in the plane of the sky.

Our 3σ upper limit of 70 mas yr^{-1} on the SGR proper motion could still be consistent with a physical association of the SGR with G42.8+0.6. Indeed, the $\sim 18'$ angular separation between the SGR and the SNR center would require, for an association to hold, $18'/(70$ mas yr$^{-1}) \sim 15,500$ yr as a 3σ lower limit to the SGR/SNR age. This would point to a system significantly older than usually assumed. The age of G42.8+0.6 is rather uncertain, in view of the poorly constrained distance to the SNR (Marsden et al. 2001), and could therefore fit within such a picture. However, estimating the true age of SGR 1900+14 is very difficult. The characteristic age $\tau_c = P/2\dot{P}$ of the SGR, derived under standard magnetodipole braking assumptions, is as low as ~ 1300 yr (Woods & Thompson 2006). Such a value should be treated with caution, since the spin-down rate of SGR 1900+14 has been observed to undergo significant variations (but remaining very high, in the 6–20×10^{-11} s^{-1} range, throughout 20 years of observations; Woods & Thompson 2006). The observed $\dot{P}$ changes showed no obvious correlation with the variability in the SGR persistent emission nor with bursting activity, and, ultimately, the physical mechanisms driving the peculiar SGR spin-down evolution are not understood.

In any case, it has been argued (Kouveliotou et al. 1999; Thompson et al. 2000) that τ_c could underestimate the true age of the SGR. For instance, additional torque due to a charged particle wind—leading to a different long-term evolution with regard to pure magnetodipole torque (which implies $\dot{P} \propto P^{-1}$)—could play an important role. Thompson et al. (2000) calculated the braking due to such wind torque (resulting in $\dot{P} \propto P$) and estimated that the true age of the SGR could be of ~ 4000 years. Even such a revised age seems uncomfortably low to be consistent with a 3σ lower limit of 15,500 years. An additional hypothesis would be required, namely that we are observing SGR 1900+14 in a transient phase of accelerated spin-down (Kouveliotou et al. 1999; Thompson et al. 2000), lasting a fraction ϵ of the SGR true age τ. Setting $\tau = \epsilon^{-1} P/\dot{P}$, our lower limit to the SGR age translates to a 3σ upper limit to ϵ of ~ 0.15. Unless such a behavior is unique to SGR 1900+14, this would imply that SGRs spend a large majority of their life in a "slowly braking" regime (which ignores the braking due to their expected, very high dipole fields). Furthermore, slowly braking SGRs should outnumber, by a factor ϵ^{-1}, SGRs with accelerated braking such as SGR 1900+14 (Thompson et al. (2000) proposed to identify such slowly braking SGRs with AXPs; however, AXPs do not display, on average, a significantly slower spin-down than SGRs).

We believe that these issues are not worth further consideration. In view of the above difficulties in associating SGR 1900+14 with G42.8+0.6 (taking into account our upper limit to the SGR proper motion) and of the high chance alignment probability for the two systems, Occam's razor argues against any physical link between them.

Such a conclusion adds further support to the association of SGR 1900+14 with the nearby cluster of massive stars discovered by Vrba et al. (2000). Morphological evidence of a physical interaction of the gas surrounding the SGR and the cluster's stars (Wachter et al. 2008) argues against a simple chance alignment for the two systems, suggesting that SGR 1900+14 originated within the cluster.

Of course, this leaves open the question of the fate of the remnant left by the supernova in which the SGR originated. Dense gas and dust clouds associated with the massive star cluster could hide the SNR emission. If the birthplace of the SGR lies within the star cluster, a rather tight upper limit to its space velocity may be set. The angular separation of ~ 12 arcsec (Vrba et al. 2000) between the position of the SGR and the center of the cluster implies a projected velocity of 86 $d_{15}\,\tau_{10}^{-1}$ km s^{-1} for the neutron star, where d_{15} is the distance in units of 15 kpc and τ_{10} is the age in units of 10 kyr. Unless the SGR velocity is almost aligned along the LOS, this estimate is somewhat at odds with one of the basic expectations of the magnetar model. As discussed by Duncan & Thompson (1992), suppression of convection due to the high magnetic field should give rise to anisotropies in the core-collapse process, resulting in a very high recoil velocity for the newborn neutron star (~ 1000 km s^{-1}). We note that, to date, no evidence of a high space velocity of any magnetar candidate has been found.

In this context, a physical association of SGR 1806–20 with a nearby cluster of massive stars (Fuchs et al. 1999) indirectly becomes more robust. The same is true for other magnetar candidates, namely CXO J164710.2–455216 (Muno et al. 2006) and possibly 1E 1048.1–5937 (Gaensler et al. 2005), although a revised distance estimate by Durant & van Kerkwijk (2006) argues against the latter association. This mounting evidence that a sizeable fraction of the magnetar family had very massive progenitors raises several questions concerning magnetar origin and, more generally, neutron star formation in core-collapse supernovae. Is there any link between the progenitor mass and the generation of high magnetic fields in their compact remnants? Which channels lead to the formation of young neutron stars as diverse as magnetars (*B*-field $\sim 10^{14}$ G; see, e.g., Mereghetti 2008), energetic "standard" radio pulsars (*B*-field $\sim 10^{12}$ G), and Central Compact Objects (*B*-field $\leqslant 10^{11}$ G; see, e.g., De Luca 2008)? What is the maximum mass for a star to generate a neutron star?

Focusing on the case of SGR 1900+14, more detailed investigations of the compact star cluster would be extremely useful, in order to assess the number and class of its components and thus to estimate its age. Although this is a rather difficult task, in view of the large reddening and the crowded region, it would be very rewarding since it would set a lower limit to the mass of the progenitor of the SGR.

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