On the proper motion of AXP 1E2259+586

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ABSTRACT

1E2259+586 belongs to the group of anomalous X-ray pulsars (AXP) which are thought to be magnetars. Accurate measurements of the proper motion for these interesting objects have not been made. In this work we use the data obtained by satellites ROSAT, Chandra and XMM-Newton taken in a period of 12 years to measure the change in position of 1E2259+586 with respect to the three field sources. Our work yielded an upper limit on the proper motion of \( \sim 170 \text{ mas/yr} \) which corresponds to a transverse speed of \( 2500 \text{ km s}^{-1} \), for an assumed distance of 3 kpc. We also used this upper limit to put a lower limit on the age of the CTB 109 of \( \sim 6 \text{ kyr} \), assuming they are associated. The consistency of right ascension and declination measurements by different satellites suggest that we can average these measurements to get the best to date position of 1E2259+586.

Subject headings: Anomalous X-ray Pulsars: 1E2259+586 – AXPs: proper motion – stars: magnetars

1. Introduction

Magnetars (AXPs & SGRs) being neutron stars, must be born during core-collapse supernovae events. Hence a supernova remnant is expected to be around. Sure enough 1E2259+586 is associated with CTB109 and AXP 1845-0258 with SNR G29.6+0.1 (Woods & Thompson 2004). These associations assume magnetar kick-velocities are similar to those...
of radio pulsars. It would be very attractive to measure some magnetar proper motions directly. This work aims to do that. We have made use of the published and archival X-ray data to measure the proper motion of 1E2259+586.

In order to eliminate pointing accuracy uncertainties of the satellites we measured the position of 1E2259+586 relative to other X-ray point-sources in the same field. In Table 1 we list the archival X-ray observations where we could identify the right ascension ($\alpha$) and declination ($\delta$) difference between 1E2259+586 and the three reference sources.

2. Observations

Since its first discovery Anomalous X-ray Pulsar (AXP) 1E2259+586 has been observed with various X-ray missions many times. These observations started as early as Einstein and continued all the way to state-of-the-art satellites like Chandra and XMM-Newton. For this work we choose the observations that satisfy the following criteria; 1) Data taken by detectors that have high spatial resolution ($\sim 10''$), 2) All three reference sources (see Fig. 1) are in the field of view, 3) Exposure is long or the detector is sensitive enough so that all three reference sources are detected. In Table 1 we list the observations and the name of their respective observatories that we have used to get the positions of three selected sources together with the position of 1E2259+586.

In order to get the positions of the selected sources in the field of view of the pulsar we extracted unbinned images of all five observations. For data sets obtained with ROSAT PSPC and HRI, and Chandra ACIS we used the CIAO (version 3.2) tool WAVDETECT\(^1\) to detect all sources in the field of view. For XMM-Newton observation we used the SAS (version 6.1.0) tool EBOXDETECT that performs a sliding box detection, using locally estimated background (see SAS data analysis threads web page\(^2\)). Although using WAVDETECT on ROSAT HRI will not yield accurate Point Spread Function (PSF) sizes, this should not effect our results because we are only interested in the central position of the sources.

\(^1\)http://asc.harvard.edu/ciao/threads/wavdetect/
\(^2\)http://xmm.vilspa.esa.es/external/xmm_sw_cal/sas_frame.shtml
3. Determining the Proper Motion of 1E2259+586

In Table 1 we show the measured coordinates of all three reference sources together with the X-ray pulsar. Each of these measurements have been done for five different times. For each observation we calculated the distances of the reference sources to the pulsar in the direction of right ascension (\(\alpha\)) and declination (\(\delta\)). The individual errors were calculated from the positional accuracies of the respective instruments. PSPC detector on board ROSAT has a spatial on-axis resolution of 25 arcsec FWHM at 0.93 keV. The other detector HRI, however, has relatively high spatial resolution of \(\sim 2''\). Later, more advanced instruments such as Chandra ACIS-S and XMM-Newton MOS have also good angular resolution. For an on-axis source ACIS-S point-spread function (PSF) is under sampled by the 0'.492\times0'.492 CCD pixels. On the other hand the EPIC-MOS camera has a spatial resolution of 5'' FWHM, which is limited by the mirrors. Since all four sources have different spectra we chose these typical limiting resolutions as the error radii. These errors were then propagated with standard error propagation to get the uncertainty on each angular separation. To each of these six data sets we made a error weighted least-squares fit with a straight line, \(y = ax + b\) (see Figure 2).

Through the described method, for each data set we found the best fit value. The parameter \(a\) (slope) was varied around its best fit value (18 mas/yr) while \(b\) was kept constant at the value determined by the best fit. For each different value of \(a\) a \(\chi^2\) value was calculated. This distribution is approximately a parabola. To calculate the combined \(\chi^2\) distribution for all three data sets that give the proper motion for \(\alpha\) (or \(\delta\)) we then added the individual \(\chi^2\)s and found the minima to get a best fit value (see Figure 3). To get the errors associated with the proper motions calculated we used the method described by Lampton et al. (1976). 1\(\sigma\) error associated with the proper motion were found by adding 10.7\(^3\) to our minimum \(\chi^2\) for total of 9 degrees of freedom and found the width of the curve at that point (Figure 3). We give the values of the best fit and it’s 1\(\sigma\) error in Table 2.

4. Absolute position of 1E2259+586

Since the data set on Table 1 represents also a summary of all the X-ray position measurements of 1E2259+586, the consistency of the right ascension, declination measurements by different satellites suggest that we can average these measurements to get the best to

\(^3\)This is the value of the reduced chi-square (\(\chi^2/\nu\)) corresponding to the probability of observing a value of chi-square larger than \(\chi^2\) with \(\nu\) degrees of freedom.
date position of 1E2259+586. The variance in the data set would also yield the error in this average position measurement. The results in (J2000) are, \( \alpha = 23^{h}01^{m}08^{s}.21 \pm 2^{s}.2 \) and \( \delta = +58^{\circ}52^{\prime}44^{\prime\prime}.8 \pm 2^{\prime\prime}.2 \). These coordinates, within the error-bars include candidates from previous searches for the optical counterpart (Hulleman et al. (2001), Hulleman et al. (2000)). Optical identifications, or upper limits are crucial for AXPs since it determines the mass and nature of the donor component, hence the energy emission mechanism.

5. Discussion

The uncertainties calculated being larger than the proper motion indicates that the available data is not sufficient to determine a definite proper motion. However, we can put an upper limit on it. The maximum angular speed 1E2259+586 can be calculated by the simple formula \( (\mu_\alpha^2 + \mu_\delta^2)^{1/2} \) (see Table 2) which gives us an upper limit on the proper motion of \( \sim 170 \) mas/yr. This together with the adopted distance of 3 kpc (Kotthes et al. 2002) gives us a maximum transverse velocity of 2500 km s\(^{-1}\). Although from the best fit values we can calculate a direction for the proper motion, the uncertainty being too high does not make the effort worthwhile.

Associations, in general, between neutron stars and SNRs are usually judged on criteria such as agreement in age/distance, positional coincidence and evidence from proper motion. Distance estimates for AXPs have relatively big uncertainties, and there is no evidence that their characteristic ages are reliable age estimators. For 1E2259+586 we have two different age estimators; the age of the host remnant (\( \sim 20 \) kyr, Rho & Petre (1997)) and also the spin-down age (\( \sim 220 \) kyr). The age derived from the SNR assumes that they are physically associated. This method is a rough estimate for the age of the SNR and depends on the assumed spectral model for the X-ray emitting gas that surrounds the remnant. Our approach gives a lower limit for the age of 1E2259+586. Although we also assume that the SNR and the pulsar are associated, we make no assumptions on the spectral properties of CTB109 and its distance. The SNR is roughly spherical in shape and 1E2259+586 is close to its geometric center. We estimated the radius of this remnant as \( \sim 1000'' \) (see Figure 1). This radius together with the measured upper limit for the proper motion gives us a lower limit on the age of the pulsar of \( \sim 6 \) kyr. This limit is consistent with all other age estimates and is not very restrictive. However it is completely independent of all other methods used to determine the age. This limit is also very close to the age \( \sim 9 \) kyr determined by Sasaki et al. (2004) from several XMM-Newton observations.

The upper limit of 2500 km s\(^{-1}\) for the proper motion is consistent with that of those expected for radio pulsars. Arzoumanian et al. (2002) calculated the velocity distribution
of radio pulsars. They find that \(\sim 15\%\) of pulsars have velocities greater than 1000 km s\(^{-1}\) and the distribution function asymptotically approaches zero beyond 700 km s\(^{-1}\) for a two component distribution. Although our upper limit is higher than all (but PSR B1552-31, (Manchester \textit{et al.} 1978)) known pulsar velocities it is right on the upper limit of those that are expected for radio pulsars.

Furthermore, birth properties of magnetars need not be the same as radio pulsars. For example, the magnetar model predicts that soft gamma repeaters may be born with velocities \(\gtrsim 1000\) km s\(^{-1}\) (e.g. see Thompson (2000)). We should also note that the velocity calculated here is a function of the distance, which is not well known and has an uncertainty \(\gtrsim 50\%\).

Another way of obtaining an estimate for the speed is to check the potential consequences high transversal velocities may cause. For instance, the speed of sound in the medium surrounding the pulsar is on the order of \(\gtrsim 5000\) km s\(^{-1}\) assuming a gas temperature of 1 MK and mean particle density of 1 cm\(^{-3}\). If 1E2259+586 had a proper motion larger than this than we would expect a shock front to form, no such thing has been detected. Also, the previous works that measured the absolute position of the pulsar for two different observations were not conclusive. The current best position (Patel \textit{et al.} 2001) when compared to the previous best position (Hulleman \textit{et al.} 2000) for 1E2259+586 yields no discrepancy within the uncertainties. Hence we conclude that the proper motion measurements that has been made in this work are the best so far. There are cases where optical sources are obscured by galactic dust absorption. Hard X-rays may be the only handle we have on the proper motion of some of these objects. However, relative proper motion measurements are usually done in optical and radio-astronomy since the requirements are: 1) there be enough sources in the field, 2) the accuracy of position measurements are high. The current observatories allows us to meet both of these criteria. Thus confirming the coming of age in X-ray astronomy.

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Fig. 1.— (Left) The region that is blown up here is shown with a box on the right hand side image. The sources around 1E2259+586 and their respective names adopted in this paper. The image is taken from Chandra observation, see Table 1. (Right) The circle approximately cocentered with SNR. The radius of the circle is 1000″, which is a rough estimate of the size of the remnant.
| Mission | ROSAT | ROSAT | Chandra | XMM-Newton | XMM-Newton |
|---------|-------|-------|---------|------------|------------|
|         | PSPC  | HRI   | ACIS    | MOS        | MOS        |
| Date    | 1991-07-09 | 1992-01-08 | 2000-01-12 | 2002-06-11 | 2002-06-21 |
| Duration (ks) | 33.37 | 22.41 | 19.13 | 52.53 | 31.05 |

Sources and their respective coordinates, ($\alpha$, $\delta$), for each observation:

|        | 1E2259+586 | E1   | E2  | E3   |
|--------|------------|------|-----|------|
|        | 345.2845   | 345.2491 | 345.1378 | 345.1785 |
|        | +58.8783   | +58.9628 | +58.8791 | +58.8416 |
|        | 345.2828   | 345.2498 | 345.1353 | 345.1784 |
|        | +58.8805   | +58.9606 | +58.8815 | +58.8430 |
|        | 345.2845   | 345.2504 | 345.1386 | 345.1809 |
|        | +58.8792   | +58.9589 | +58.8801 | +58.8430 |
|        | 345.2842   | 345.2492 | 345.1384 | 345.1804 |
|        | +58.8788   | +58.9585 | +58.8797 | +58.8426 |
|        | 345.2850   | 345.2502 | 345.1397 | 345.1809 |
|        | +58.8788   | +58.9586 | +58.8795 | +58.8414 |

Table 1: RA and DEC of selected sources around the pulsar, for different observations.
Table 2: Statistics for the simultaneous fits done for $\Delta \alpha$ and $\Delta \delta$ for each selected source, see Figure 2. We used a linear function of the form $y = ax + b$. The errors given are 1$\sigma$.

| $\chi^2$/dof | $a$ (arcsec/day) | $\Delta a$ (arcsec/day) | Proper Motion ($\mu$) (mas/yr) |
|-------------|------------------|-------------------------|-------------------------------|
| $\alpha$    | 61.2/9           | -0.000054               | 0.000285                      | 18 ± 104                      |
| $\delta$    | 9.9/9            | -0.000033               | 0.000285                      | 12 ± 104                      |
Fig. 2.— The angular distance between 1E2259+586 and the respective X-ray source in the direction of $\alpha$ (Left) and $\delta$ (Right) versus the date of the observation. The best linear fit to data is shown with a straight line in each case. We have taken out the datum for the ROSAT PSPC observation just for plotting purposes. It was, however, included in the fit.
Fig. 3.— $\chi^2$ per degrees of freedom ($\nu$) versus proper motion in the direction of $\alpha$ (Left) and $\delta$ (Right). Solid curves are the $\chi^2$ distribution of the individual fits whereas the dotted line is the distribution of all three combined (average). $\nu$ is 3 for individual fits and 9 for the combined distribution. The dashed horizontal line is the marker for the 1$\sigma$ error level. See text for the explanation.