The Proper Motion of the Neutron Star in Cassiopeia A

Tracey DeLaney and Joseph Satterfield
Physics & Engineering Department, West Virginia Wesleyan College, Buckhannon, WV 26201, USA
delaney_t@wvwc.edu

ABSTRACT

Images from the High Resolution Camera on the Chandra X-ray Observatory were used to measure the proper motion of the neutron star in Cassiopeia A over a baseline of 10 years (1999-2009). One background source and 13 quasi-stationary flocculi were chosen to register the two images. Pixel offsets between features at each epoch were measured using four different statistical methods: Gaussian fitting, centroiding, cross correlation, and the Cash statistic. In many cases the offset measurements disagree in magnitude and/or direction by as much as 1″, resulting in large uncertainties. As a result, the measurement for the motion of the neutron star is marginal at 390±400 km s⁻¹ in the southeast direction. This motion is typical of the birth velocities of young pulsars and is consistent with the inferred proper motion based on the offset of the neutron star from the center of expansion of the optical ejecta.

1. Introduction
1.1. General Background on Cas A

Cassiopeia A (Cas A; 3C 461, G111.7-2.1) is the 2nd-youngest-known supernova remnant (SNR) in the Galaxy and lies at a distance of 3.4 kpc away (Reed et al. 1995). With the discovery of light echoes from the explosion, we now know that Cas A resulted from an asymmetric type IIb explosion (Krause et al. 2008; Rest et al. 2011). One of the most exciting discoveries with the Chandra X-ray Observatory was the neutron star in Cas A (Tananbaum 1999). The neutron star does not show X-ray or radio pulsations (McLaughlin et al. 2001; Mereghetti, Tiengo, & Israel 2002) and lacks a synchrotron nebula (Hwang et al. 2004) typical of ordinary young pulsars still located within their supernova remnants (SNRs). Ho & Heinke (2009) have shown that the neutron star is successfully fitted using a low magnetic field carbon atmosphere model and emits thermal radiation from the entire surface. Furthermore, the cooling rate of the neutron star has been measured (Heinke & Ho 2010), it has a gravitational mass of M≈1.3-2 M⊙ (Yakovlev et al. 2011), and the neutrons in the core have recently become superfluid (Shternin et al. 2011).

The neutron star is offset from the well determined expansion center of the undecelerated optical ejecta by 7″ nearly due south (Fesen et al. 2006). The implied projected velocity based on this offset is about 350 km s⁻¹ (assuming an age of 330 years) which is typical of young pulsars (Lyne & Lorimer 1994). However, the offset is ≈90° from the axis defined by the northeast and southwest jets (Hwang et al. 2004) – the axis along which one might expect a “birth kick” due to supernova explosion asymmetries (Lai, Chernoff, & Cordes 2001).

The jets, however, do not provide the only symmetry axis in Cas A. The X-ray iron emission and the infrared neon emission also fall into bipolar structures to the north and south/southeast (Emis et al. 2006; Smith et al. 2009; DeLaney et al. 2010). Aligned with the north/south neon axis are gaps in the distribution of outer optical ejecta knots (Fesen et al. 2006), further supporting a roughly north-south symmetry axis. These various bipolar symmetries observed in multiple wave-
bands in the north-south direction provide an alternative predicted kick direction for the neutron star – one that agrees with the inferred motion.

Although the offset of the neutron star from the expansion center of Cas A is effectively irrefutable evidence of the direction and magnitude of motion, a simple verification of the motion of the neutron star is in order. Therefore, in this paper we report on the proper motion measurement of the neutron star using images from the High Resolution Camera (HRC) on the Chandra X-ray Observatory. In §2 we describe the observations. In §3 we discuss the image registration between epochs with the calculation of the neutron star motion presented in §4. In §5 we discuss the results from our analysis and we offer concluding remarks in §6.

2. Observations

New observations of Cas A were taken in Dec 2009 with the HRC instrument on Chandra. Care was taken to use the same pointing and roll parameters as the original 50-ks HRC observation in Dec 1999 in order to mitigate any effects from the asymmetrical point spread function. As shown in Table 1, the 2009 observations were taken over four separate days and totaled about 3 ks less than the 1999 observation. The pointing centers for the observations varied by only a few arcseconds and the roll only changed by 0.1°. Before merging the four level two event files from the 2009 observations, Gaussian fitting of the neutron star was used to determine that the registration uncertainty was less than 0.1 pixel, where 1 HRC pixel = 0.1′′1318. The 1999 data were re-processed using the same version of Ciao and CALDB as the 2009 data, including aspect correction.

3. Image Registration

3.1. Registration Sources

The original intent was to use five background sources within the field of view of the 1999 HRC image to register to the 2009 image. Four of the five sources were present on the ROSAT image of Cas A, leading us to believe that they were robust sources to use. Unfortunately, as Figure 1 shows, only one of these background sources was present in the 2009 HRC image. We have named this lone background source src2.

Therefore, we needed to use Cas A to register the 1999 and 2009 HRC images. The proper motions of the X-ray ejecta in Cas A are on the order of a few thousand kilometers per second (DeLaney et al. 2004). The X-ray proper motion measurements were made over a span of only two years and used the neutron star as the primary registration source. Therefore, there may be asymmetries or measurement artifacts in the proper motions that could result in errors of order a few hundred kilometers per second, which is on the order of the inferred velocity of the neutron star.

We then decided to use a number of quasi-stationary flocculi (QSFs). QSFs are slow-moving ($v \lesssim 500$ km s$^{-1}$) stellar wind clumps with well-determined velocities based on over 30 years of

![Fig. 1.— Background point sources in the field of view of the HRC in 1999 (left) and 2009 (right). We have named the lone background source in the 2009 image src2.](image)

![Fig. 2.— The QSFs and background point source used for image registration.](image)
Table 1
Observational Parameters

| Obs Id | Date       | RA (deg) | Dec (deg) | Roll (deg) | Livetime (sec) |
|--------|------------|----------|-----------|------------|----------------|
| 1505   | 1999 Dec 19| 350.8566 | 58.81010  | 287.1300   | 48720          |
| 11240  | 2009 Dec 20| 350.8568 | 58.81059  | 287.0352   | 12914          |
| 12057  | 2009 Dec 13| 350.8570 | 58.81053  | 287.0350   | 10884          |
| 12058  | 2009 Dec 16| 350.8571 | 58.81051  | 287.0349   | 9224           |
| 12059  | 2009 Dec 15| 350.8568 | 58.81058  | 287.0351   | 12801          |

optical observations (Kamper & van den Bergh 1976; van den Bergh & Kamper 1985). DeLaney et al. (2004) found that many of the optical QSFs had direct X-ray counterparts and that X-ray QSFs could be identified based on their spectra and dynamics. Thirteen QSFs were chosen based on their brightness, isolation in the X-ray image, availability of optical and/or X-ray proper motion information, and position on the image – we wanted to have about equal numbers of QSFs above/below and left/right of the neutron star. These QSFs are identified in Figure 2.

3.2. Measuring Offsets between Epochs

There are many statistical techniques for finding the “center” of an emission clump or determining the offset between two clumps. All of these techniques require the setting of some sort of bounding box over which the statistical calculations are performed. In addition, there are a range of binning and smoothing parameters that can be applied to the images before they are analyzed.

To determine how much of an effect the bounding box, binning, and smoothing had on our analysis, we used the Gaussian fitting routines IMFIT and JMFIT within the Astronomical Image Processing System (AIPS) with a range of these parameters. IMFIT and JMFIT use 2-dimensional elliptical Gaussians and are able to solve for a constant, linear, or quadratic two-dimensional baseline surface. Images of each region at each epoch were made with a range of binning from none to a factor of 4 and with a range of Gaussian smoothing sizes from no smoothing to smoothing over 2'.1. Bounding boxes ranged in size from twice the size of the clump to hugging the clump tightly and a range of parameters were chosen to describe the baseline surface. The two AIPS Gaussian fitting routines were very robust in reporting clump centers with the poorest standard deviation of about 0.5 HRC pixel (0'.0659) for QSF4 and src2.

We repeated the analysis above using the centroiding feature within SAOImage DS9. Centroiding was quite robust, with similar standard deviations to the Gaussian fitting. However, in many cases the clump centers were significantly different from those determined based on Gaussian fitting. This was to be expected because centroiding and Gaussian fitting weight image data quite differently.

Our final two statistical measures computed the registration offsets between each epoch directly. For the first technique, the 1999 image of each region was shifted in $x$ and $y$ with respect to the 2009 image and the Cash statistic (Cash 1979) was computed between the two images at each shift position. The amount of the shifting and the size of the box over which the Cash statistic was computed varied from 20-80 HRC pixels ($2'.6 - 10'.5$) depending on the size of the region and nearby confusing emission structures. Finally, the AIPS routine CONVL was used to determine the offset between images at each epoch using cross correlation. We again found that the solutions were highly dependent on the statistical method used with much less dependence on binning, smoothing, and bounding box.

The single most complicating factor in these position and offset measurements is that the QSFs and src2 changed morphology between 1999 and 2009, as shown in Figure 3. As a result, the different statistical measures varied not only in mag-
magnitude of offset between 1999 and 2009, but in direction of offset as well with the largest difference being about 8 HRC pixels (1′′). Columns 5-12 of Table 2 show the results of the individual statistical techniques. The offsets reported for each region are averaged over all of the binning, smoothing, and bounding box parameters applied as discussed above and are reported in HRC pixels. The x- and y-offsets indicate how far the 1999 region is shifted from the 2009 region with negative numbers indicating offsets to the east or south.

We also report in Table 2 the X-ray counts for each region as a measure of brightness. In principle, one would expect low brightness regions to have a larger uncertainty than high brightness regions. However, the morphology changes so dominated the offset measurements that there was no correlation between counts and measurement scatter.

In order to determine the final registration solution between 1999 and 2009, each of the x- and y-offset measures for each region were corrected for their 10-year proper motion based on either the optical or X-ray measurement (van den Bergh & Kamper 1983; DeLaney et al. 2004). The 10-year proper motions are indicated in columns 3 and 4 of Table 2. About half of the QSFs had optical counterparts with very well determined motions such that the position error over 10 years is less than 1 HRC pixel. The other half of the QSFs had only X-ray proper motions with larger errors, as much as several pixels over 10 years (DeLaney et al. 2004). The proper-motion-corrected offsets were then averaged together for each region with the standard deviation of the mean being used as the estimate of uncertainty.

The weighted mean x- and y-offsets were calculated using the individual mean offsets for each region with the uncertainties used as the weights. The weighted standard deviation is used as the final estimate for the uncertainty in image registration. The final image registration solution is to shift the 2009 image $-0.1 \pm 1.5$ pixels in $x$ and $-1.1 \pm 0.9$ pixels in $y$ to best match up with the 1999 image. Figure 4 shows the mean offsets and uncertainties for each of the QSFs and src2. Also shown is the final registration solution, represented by the $\times$ and the final uncertainty estimate, represented by the ellipse.

4. Neutron Star Motion

The neutron star position and offsets were measured in the same way as for the QSFs and src2 using the same range of binning, smoothing, and
### Table 2

**Data used to register images.**

| Region | Counts | Proper Motion* | Cash Statistic | Gaussian | Centroid | Cross Correlation | Mean | Uncertainty |
|--------|--------|----------------|----------------|----------|----------|-------------------|------|-------------|
|        |        | $x$ | $y$ | $x$-offset | $y$-offset | $x$-offset | $y$-offset | $x$-offset | $y$-offset | $x$-offset | $y$-offset | $x$-offset | $y$-offset | $x$-offset | $y$-offset | $x$-offset | $y$-offset | $x$-offset | $y$-offset |
| src2   | 2039   | 0.00 | -4.00 | 2.20 | 3.90 | 1.24 | 1.90 | 2.00 | -2.92 | 1.36 | -0.28 | 0.50 | 1.89 |
| 1      | 8361   | -7.59 | -0.76 | -2.75 | -4.75 | -4.65 | -3.32 | 0.17 | 0.23 | 0.26 | -0.15 | 5.92 | -1.24 |
| 2      | 8336   | -0.27 | 1.18 | 2.00 | 1.50 | -2.65 | -1.12 | -0.24 | -0.91 | 0.10 | 0.88 | 0.07 | -1.09 |
| 3      | 2771   | -0.27 | 1.18 | 0.75 | -0.25 | -2.29 | -0.13 | -0.24 | -0.68 | 0.61 | 0.24 | 0.02 | -1.39 |
| 4      | 908    | -1.52 | -0.76 | 1.25 | 0.75 | -2.62 | -0.06 | 5.92 | 0.61 | -0.92 | -6.00 | 2.43 | -0.42 |
| 5      | 842    | 3.79 | -0.76 | -2.00 | 0.00 | -3.15 | -0.67 | -4.14 | -0.38 | 2.52 | 0.95 | -5.48 | 0.74 |
| 6      | 1682   | 2.28 | 1.52 | 0.00 | 0.75 | -2.43 | -1.53 | 0.30 | 0.15 | 1.06 | -0.38 | -2.55 | -1.77 |
| 7      | 3044   | -0.73 | 1.67 | 2.25 | 1.75 | 0.87 | 2.33 | -4.14 | -0.76 | 1.02 | 0.73 | 0.73 | -0.66 |
| 8      | 3103   | 1.52 | 1.52 | 1.00 | 0.75 | 2.04 | -3.25 | 0.80 | 0.38 | 1.55 | -0.08 | -0.15 | -2.07 |
| 9      | 3560   | -1.75 | 0.90 | -0.50 | 1.00 | -0.77 | -5.64 | -5.92 | -1.29 | 0.61 | 2.04 | 0.11 | -1.87 |
| 10     | 3412   | 3.79 | 3.79 | 2.50 | 1.75 | 4.96 | -1.14 | -0.12 | -0.46 | -0.09 | 0.06 | -1.98 | -3.74 |
| 11     | 6103   | -0.07 | 0.33 | -3.25 | -0.25 | 3.21 | -1.17 | -0.18 | -0.30 | -0.93 | 0.11 | -0.22 | -0.73 |
| 12     | 2840   | 0.17 | 1.33 | -0.75 | 1.00 | -3.49 | -5.54 | 0.36 | 0.38 | -2.74 | 1.63 | -1.83 | -1.96 |
| 13     | 5760   | 1.37 | 1.87 | 0.25 | -1.00 | 0.83 | -3.00 | -4.73 | -0.23 | 0.08 | 1.99 | -2.26 | -2.43 |
| NS     | 2493   | 1.00 | -0.25 | 1.10 | -0.41 | 2.07 | 0.30 | 1.51 | -0.23 | 1.42 | -0.15 | 0.49 | 0.31 |

Note.— Measurements are in pixels (1 pixel=$0.1318''$). Data indicate how far the 1999 region is offset from the 2009 region. Negative numbers indicate offsets to the east or south.

*10-year motions based on optical [van den Bergh & Kamper 1985](#) or X-ray (italic, [DeLaney et al. 2002](#)) data.

bCorrected for the proper motions indicated in columns 3 and 4.

cStandard deviation of the mean of the four measurements except for the neutron star where just the standard deviation is reported.
bounding box parameters. The individual $x$- and $y$-offsets were averaged together and standard deviations computed. These are shown in the last row of Table 2. We note that if we simply do not apply any registration corrections, the neutron star would appear to move almost due east.

The final solution for the motion of the neutron star was corrected for the registration solution and the final uncertainties in the motion are found by adding in quadrature the registration uncertainties and the measured offset uncertainties. This results in a proper motion of $-1.6 \pm 1.6$ pixels ($-0.02 \pm 0.02$ arcsec/yr) in $x$ and $-0.9 \pm 1.0$ pixels ($-0.01 \pm 0.01$ arcsec/yr) in $y$. At a distance of 3.4 kpc (Reed et al. 1995), this results in a velocity of 387 \pm 401 km s$^{-1}$ at $121^\circ \pm 47^\circ$ (southeast), which is consistent with the inferred motion of 350 km s$^{-1}$ (Rest et al. 2011) at a position angle of 169$^\circ \pm 8.4^\circ$ (Fesen et al. 2006). Figure 5 shows the final solution and uncertainty for the proper motion of the neutron star and Figure 6 shows final registered images of the neutron star in 1999 and 2009.

5. Discussion

The motion of the neutron star in Cas A is typical of the birth velocities of young pulsars, which range from $\sim 200 - 500$ km s$^{-1}$ (Chatterjee et al. 2005). A number of physical mechanisms have been suggested to account for these velocities, including the disruption of binaries through mass loss in supernovae (Iben & Tutukov 1996) and the electromagnetic rocket effect (Harrison & Tademaru 1975). The most likely explanation, though, is a birth kick imparted to the pulsar through asymmetries in the supernova explosion (Lai, Chernoff, & Cordes 2001). There is currently no consensus regarding the details of the core-collapse explosion process and the resulting asymmetries. Some models favor magnetohydrodynamic instabilities to produce jets which drive a bipolar supernova explosion and impart birth kicks parallel to the jet axis (Wheeler, Meier, & Wilson 2002). In other models, asymmetric neutrino emission, which is mediated by high magnetic fields, drives the birth kick (Arras & Lai 1999).

We now know that the neutron star has a low magnetic field (Hu & Heinke 2009) with a motion that is roughly orthogonal to the jet axis. We know that Cas A’s explosion was asymmetric (Rest et al. 2011) and that there are a number of axisymmetric ejecta alignments also roughly orthogonal to the jet axis (Ennis et al. 2006; Smith et al. 2009; DeLaney et al. 2010), including a gap in the outer ejecta knot distribution (Fesen et al. 2006). Careful mass estimates combined with modeling reveal that Cas A, as a whole, is moving at about 700 km s$^{-1}$ to the north (Hwang & Laming 2012). Therefore, hydrodynamic kick mechanisms that do not invoke strong magnetic fields or misaligned jets and that only require a modest ejecta mass and velocity asymmetry are preferred, such as those of Nordhaus et al. (2010, 2012).

Fig. 6.— Registered 1999 and 2009 images of the neutron star.
6. Conclusion

We have attempted to directly measure the proper motion of the neutron star in Cas A over a baseline of 10 years using data from the HRC instrument on Chandra. Due to a paucity of background point sources, we were forced to use the QSFs in Cas A to register the 1999 image to the 2009 image. The QSFs are not point sources, are in motion, and changed morphology over the 10-year span. Thus, our measurement of the neutron star motion is marginal at 390 ± 400 km s\(^{-1}\) in the southeast direction. This motion agrees with the inferred motion based on the offset of the neutron star from the expansion center of Cas A. Supernova models that attempt to reproduce the kick velocity of the neutron star must also account for the direction of the kick, which is roughly orthogonal to the northeast-southwest jet axis in Cas A.

This work was supported by NASA through Chandra grant GO0-11089X and by the NASA-West Virginia Space Grant Consortium. We thank Shami Chatterjee for his assistance in preparing the proposal for the 2009 HRC observations and for reviewing this paper prior to submission.

Facilities: CXO(HRC)

REFERENCES

Arras, P. & Lai, D. 1999, ApJ, 519, 745
Cash, W. 1979, ApJ, 228, 939
Chatterjee, S., Vlemmings, W. H. T., Brisken, W. F., Lazio, T. J. W., Cordes, J. M., Goss, W. M., Thorsett, S. E., Fomalont, E. B., Lyne, A. G., & Kramer, M. 2005, ApJ, 630, L61
DeLaney, T., Rudnick, L., Fesen, R., Jones, T. W., Petre, R., & Morse, J. A. 2004, ApJ, 613, 343
DeLaney, T., Rudnick, L., Stage, M. D., Smith, J. D., Isensee, K., Rho, J., Allen, G. E., Gomez, H., Kozasa, T., Reach, W. T., Davis, J. E., & Houck, J. C. 2010, ApJ, 725, 2038
Ennis, J. A., Rudnick, L., Reach, W. T., Smith, J. D., Rho, J., DeLaney, T., Gomez, H., & Kozasa, T. 2006, ApJ, 652, 376
Fesen, Robert A., Hammel, Molly C., Morse, Jon, Chevalier, Roger A., Borkowski, Kazimierz J., Dopita, Michael A., Gerardy, Christopher L., Lawrence, Stephen S., Raymond, John C., & van den Bergh, Sidney 2006, ApJ, 645, 283
Harrison, E. & Tademaru, E. 1975, ApJ, 201, 447
Heinke, Craig O. & Ho, Wynn C. G. 2010, ApJ, 719, L167
Ho, Wynn C. G. & Heinke, Craig O. 2009, Nature, 462, 71
Hwang, Una & Laming, J. Martin 2012, ApJ, 746, 130
Iben, I. & Tutukov, A. 1996, ApJ, 456, 738
Kamper, K. & van den Bergh, S. 1976, ApJS, 32, 351
Krause, O., Birkmann, S. M., Usuda, T., Hattori, T., Goto, M., Rieke, G. H., & Misselt, K. A. 2008, Science, 320, 1195
Lai, Dong, Chernoff, David F., & Cordes, James M. 2001, ApJ, 549, 1111
Lyne, A. & Lorimer, D. 1994, Nature, 369, 127
McLaughlin, M. A., Cordes, J. M., Deshpande, A. A., Gaensler, B. M., Hankins, T. H., Kaspi, V. M., & Kern, J. S. 2001, ApJ, 547, L41
Mereghetti, S., Tiengo, A., & Israel, G. L. 2002, ApJ, 569, 275
Nordhaus, J., Brandt, T. D., Burrows, A., Livne, E., & Ott, C. D. 2010, Phys. Rev. D, 82, 103016
Nordhaus, J., Brandt, T. D., Burrows, A., & Almgren A. 2012, MNRAS, 423, 1805
Reed, J. E., Hester, J. J., Fabian, A. C., & Winkler, P. F. 1995, ApJ, 440, 706
Rest, A., Foley, R. J., Sinnott, B., Welch, D. L., Badenes, C., Filippenko, A. V., Bergmann, M., Bhatti, W. A., Blondin, S., Challis, P., Damke, G., Finley, H., Huber, M. E., Kasen, D., Kirshner, R. P., Matheson, T., Mazzali, P., Minniti, D., Nakajima, R., Narayan, G., Olsen, K., Sauer, D., Smith, R. C., & Suntzeff, N. B. 2011, ApJ, 732, 3

Shternin, Peter S., Yakovlev, Dmitry G., Heinke, Craig O., Ho, Wynn C. G., & Patnaude, Daniel J. 2011, MNRAS, 412, L108

Smith, J. D. T., Rudnick, L., Delaney, T., Rho, J., Gomez, H., Kozasa, T., Reach, W. T., & Isensee, K. 2009, ApJ, 693, 713

Tananbaum, H. 1999, IAU Circ., 7246, 1

van den Bergh, S. & Kamper, K. 1985, ApJ, 293, 537

Yakovlev, Dmitry G., Ho, Wynn C. G., Shternin, Peter S., Heinke, Craig O., & Potekhin, Alexander Y. 2011, MNRAS, 411, 1977

Wheeler, J. Craig, Meier, David L., & Wilson, James R. 2002, ApJ, 568, 807

Willingale, R., Bleeker, J. A. M., van der Heyden, K. J., & Kaastra, J. S. 2003, A&A, 398, 1021

This 2-column preprint was prepared with the AAS L\TeX \textsc{macros} v5.2.