DIRECT MEASUREMENT OF NEUTRON STAR RECOIL IN THE OXYGEN-RICH SUPERNOVA REMNANT PUPPIS A

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ABSTRACT

A sequence of three Chandra X-Ray Observatory High Resolution Camera images taken over a span of five years reveals arcsecond-scale displacement of RX J0822–4300, the stellar remnant (presumably a neutron star) near the center of the Puppis A supernova remnant. We measure its proper motion to be $0.165''/yr$ toward the west-southwest. At a distance of 2 kpc, this corresponds to a transverse space velocity of $\sim1600$ km s$^{-1}$. The space velocity is consistent with the explosion center inferred from proper motions of the oxygen-rich optical filaments and confirms the idea that Puppis A resulted from an asymmetric explosion accompanied by a kick that imparted roughly $3\times10^{49}$ ergs of kinetic energy (some $3\%$ of the kinetic energy for a typical supernova) to the stellar remnant. We discuss constraints on core-collapse supernova models that have been proposed to explain neutron star kick velocities.

Subject headings: astrometry — ISM: individual (Puppis A) — stars: neutron — supernova remnants — supernovae: general — X-rays: individual (RX J0822–4300)

1. INTRODUCTION

There has long been broad consensus that core-collapse supernovae (SNe), the explosions of massive progenitors that produce Type II, Ib, and Ic SN events at least, leave behind a compact stellar remnant, either a neutron star or a black hole. Early on, this model was marred by the paucity of observed compact objects associated with supernova remnants (SNRs). The discovery in recent years of numerous compact X-ray sources associated with SNRs, especially with the oxygen-rich SNRs that are presumably the young remnants of core-collapse SNe, has removed this blemish (see, e.g., Manchester 2001 for a recent review). Compact stellar remnants have been identified near the centers of all three of the known oxygen-rich SNRs in the Galaxy—Cas A (Tananbaum 1999; Chakrabarty et al. 2001), Puppis A (Petre et al. 1996), and most recently G292.0+1.8 (Hughes et al. 2001; Tananbaum 1999; Chakrabarty et al. 2001), Puppis A (Petre et al. 2001). Past optical studies of the most prominent ejecta-dominated filaments show that they are concentrated in the northeast quadrant of the remnant, and that their motions are northward and eastward, consistent with undecelerated expansion from a common center (Winkler & Kirshner 1985; Winkler et al. 1988).

The present measurement of the stellar remnant’s rapid motion to the west-southwest completes a picture of asymmetric ejecta and neutron star recoil resulting from a core-collapse SN.

As the original version of this paper was nearing completion, we became aware of a paper by Hui & Becker (2006a, hereafter HB06) that presented a similar analysis based on two of the three Chandra observations used here. While the HB06 result is qualitatively similar to our own, our analysis leads to a more precise measurement and a significantly higher velocity for RX J0822–4300. We compare their methods with our own in §3.5.

2. OBSERVATIONS

The compact X-ray source near the center of Puppis A, RX J0822–4300, was observed with the HRC-I in 1999 December (ObsID 749), and again with the HRC-S in 2001 January (ObsID 1851). We repeated the earlier of these previous observations, using the HRC-I, on 2005 April 25 (ObsID 4612). For all three observations, RX J0822–4300 was placed essentially on axis for the High Resolution Camera (HRC) on the Chandra X-Ray Observatory. Past optical studies of the most prominent ejecta-dominated filaments show that they are concentrated in the northeast quadrant of the remnant, and that their motions are northward and eastward, consistent with undecelerated expansion from a common center (Winkler & Kirshner 1985; Winkler et al. 1988).

The present measurement of the stellar remnant’s rapid motion to the west-southwest completes a picture of asymmetric ejecta and neutron star recoil resulting from a core-collapse SN.
By great good luck, there are two additional point sources quite close to RX J0822−4300, almost optimally situated for a proper-motion study. The closer, which we refer to as star A, is located 2.7′ to the southwest of the stellar remnant; the other, star B, is 5.4′ to the northeast. Both coincide with $V \sim 13$ mag stars included in the UCAC2 astrometric catalog, with precisely measured (within 15–24 mas) positions and proper motions. Therefore, it is possible to use these stars as fiducial sources to provide a precise absolute-coordinate system for the image at each epoch.

For each of the three HRC images, we first identified the sources and measured their positions using the standard wavdetect routine in the Chandra Interactive Analysis of Observations (CIAO) software package (ver. 3.3). RX J0822−4300 and both fiducial stars were detected with high signal-to-noise ratios (>5 $\sigma$) in all three observations, with positions within 0.6″ of the UCAC2 catalog positions. There can be no doubt that the association of the X-ray sources with the UCAC2 stars is correct. In addition, there is another, very faint, X-ray source in the field at a position only 2.0″ from RX J0822−4300 and coincident within 0.5″ with a third UCAC2 star (star C). This source was detected at the ~3 $\sigma$ level in the first two Chandra observations (1999 and 2001), but the detection was extremely marginal (~5 counts ≤ 2 $\sigma$) in the 2005 observation. In order to maintain consistency, we did not use it for the astrometry in any of the images.

Relevant data for all three stars, extracted from the UCAC2 catalog, appear in Table 2. All three also appear in the 2MASS catalog (Cutri et al. 2003) at positions consistent with those in the UCAC2 but with lower precision. In Figures 1 and 2, respectively, we show the central region of an image from the 2005 HRC-I observation with the sources marked and the identical field in an exposure with the sources marked and the identical field in an exposure time and subtracts one from the next.

The absolute aspect of Chandra HRC images may be subject to uncertainty of order 0.5″, however, so we have gone to considerable effort to achieve the highest accuracy possible in the astrometry, based on the fiducial stars A and B. We discuss below two techniques, the first a simple translation from one epoch to the other (applicable for the HRC-I images only), and the second involving transformation of all three images to an absolute world coordinate system based on the optical positions for the fiducial stars. Both techniques begin with precise measurement of the X-ray positions of the NS and stars A and B on each HRC image, discussed in §3.1. The subsequent sections describe the two transformation techniques and proper-motion measurements. Since the measurement involves pushing HRC astrometry to its limits, we describe these steps in some detail.

3. Precise Astrometry and Proper-Motion Measurement

As a preface to this section, we note that the proper motion of RX J0822−4300 (which we refer to more succinctly as the neutron star [NS]) is apparent in the data. Simple comparison between images based on the original level-2 event files with the nominal aspect shows a displacement of order 1″ west, and slightly south, from the 1999 December HRC-I observation to the one in 2005 April. The difference is noticeable by blinking the two images and is even more apparent when one scales the images by the exposure time and subtracts one from the next.

The absolute aspect of Chandra HRC images may be subject to uncertainty of order 0.5″, however, so we have gone to considerable effort to achieve the highest accuracy possible in the astrometry, based on the fiducial stars A and B. We discuss below two techniques, the first a simple translation from one epoch to the other (applicable for the HRC-I images only), and the second involving transformation of all three images to an absolute world coordinate system based on the optical positions for the fiducial stars. Both techniques begin with precise measurement of the X-ray positions of the NS and stars A and B on each HRC image, discussed in §3.1. The subsequent sections describe the two transformation techniques and proper-motion measurements. Since the measurement involves pushing HRC astrometry to its limits, we describe these steps in some detail.

3.1. Nominal X-Ray Positions

For the final analysis we reprocessed the Chandra level-1 event files to incorporate the latest degapping and tap-ringing corrections. We then used the Chandra ray-tracing and simulation (ChaRT/MARX) routines to generate off-axis point-spread functions (PSFs) appropriate for each of the three sources at each epoch, following the ChaRT threads “Using MARX to Create an Event File”

| Designation | R.A. (J2000.0) | Decl. (J2000.0) | $\sigma_{\text{R.A.}}$ (mas) | $\sigma_{\text{Decl.}}$ (mas) | $\mu_{\text{R.A.}}$ (mas yr$^{-1}$) | $\mu_{\text{Decl.}}$ (mas yr$^{-1}$) | Distance from NS (arcmin) |
|-------------|---------------|----------------|-------------------|-------------------|------------------|------------------|------------------|
| A           | 13302738      | −43 02 03.64   | 15                | 15                | −16.0 ± 5.2      | −1.7 ± 5.2       | 2.7              |
| C           | 13302743      | −43 01 28.34   | 15                | 15                | −65.5 ± 4.7      | −7.0 ± 4.7       | 2.0              |
| B           | 13520024      | −42 57 59.36   | 24                | 15                | −4.2 ± 5.2       | 14.8 ± 5.2       | 5.4              |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. These values are taken from the VizieR Online Data Catalog, 1289, 0 (N. Zacharias et al., 2003).

$^a$ Angular separation from the central neutron star RX J0822−4300.
and “Creating an Image of the PSF,” and normalized these to match the observed counts in each image. We then followed the CIAO/Sherpa thread “Using a PSF Image as the Convolution Kernel” to obtain the best-fit position for each source. This procedure convolves the appropriate PSF with a source model and varies the model parameters to achieve the best match to the data. For the NS and star A we used the original (unbinned) data with a scale of 0.1318” pixel⁻¹, but for star B we binned the data (and the matching PSF) 2 × 2.

As a source model we used a narrow Gaussian with FWHM fixed at 1 pixel (≈ 0.13”) (much less than the PSF width, even for a near-on-axis source), and varied four parameters: x- and y-position (right ascension and declination, respectively), source strength, and (constant) background level. Convolving this model with the appropriate PSF matches the original data well in all cases. We also experimented with varying the width of the Gaussian and found that the fits are insensitive to the choice of FWHM as long as it is ≤ 3 pixels. There is no evidence for a finite extent to the NS source (nor for either of the stellar sources). In Figure 3 we show an example of one of the position fits, for star A at the 2005 epoch.

The results of the position fits for all three sources (based on the nominal aspect solution) at all three epochs are given in Table 3. All are based on fits like the one illustrated in Figure 3. The uncertainties represent the 1 σ (68% confidence) limits for the source position along the x- and y-axes. To obtain these, we used Sherpa to calculate the Cash (1979) statistic over a grid and used an increment of 2.3 above the minimum as the estimate of the 1 σ confidence limit for a model with two “interesting” parameters (Press et al. 1992, p. 684). An example of a Cash-statistic contour plot resulting from this procedure is shown in Figure 3d. We note that the contours are not circular; when projecting along a different axis (as we do in § 3.4) we used the actual values appropriate for that direction, as measured graphically on these plots.

3.2. Method 1: Simple Translations

The simplest approach to measuring the NS proper motion is a two-dimensional translation of the image from the second epoch relative to the first, based on the fiducial stars. If all aspects of the instrument and the data train are identical, this ought to bring the fiducial stars into alignment. But translation alone is only modestly successful in aligning stars A and B in the pair of images from the two HRC-I epochs. Even after correcting for the (small) proper motions of the stars (taken from the UCAC2) between epochs, we find shifts for stars A and B that differ by (0.95” ± 0.31”, −0.71” ± 0.42”) in x and y, respectively. An average shift weighted inversely to the variance is dominated by the shift for the more nearly on-axis star A and leads to a change in the NS position of (−0.71” ± 0.12”, −0.25” ± 0.20”) in right ascension and declination, respectively, from epoch 1998.98 to 2005.32, or proper motion 0.141” ± 0.024 yr⁻¹ at an angle of 20° ± 14° south of due west. The uncertainties are purely formal, based on uncertainties in the position fits for stars A and B, the (much smaller) uncertainties in the proper motions for the optical stars, and the (negligible) uncertainties in the position fit for the NS at the two epochs (all as given in Table 3). We did not attempt a similar pure translation between the HRC-S and HRC-I images, since there is a known small rotational offset between the HRC-S and HRC-I, and possibly other small systematic effects as well (R. Kraft 2007, private communication).

3.3. Method 2: Transformation to an Absolute Frame

A more sophisticated technique follows precise measurement of the X-ray positions of the NS and stars A and B on each HRC image (§ 3.1) with transformation of both HRC images to a common absolute world coordinate system (WCS) based on the cataloged optical positions for stars A and B. Then the NS position at each epoch, its motion between epochs, and uncertainties in these quantities may be determined from the transformations. We assume that the “true” positions for stars A and B are those for the optical stars given by the UCAC2, corrected for proper motion to the appropriate epoch. These are also given in Table 3. We then calculate the transformation so that the measured X-ray positions will exactly match the optical ones at each epoch.

We assume a linear transformation that involves four parameters: translations in x and y (tx, ty), rotation through an angle θ, and a uniform change in scale by a factor r. With only two fiducial points it is straightforward to calculate a unique transformation analytically. The transformation parameters are determined from (xA, yA), (xB, yB), the x- and y-positions for stars A and B as measured in an HRC image, and (xNS, yNS), the reference positions from the UCAC2 at the same epoch. The transformation is calculated by

\[
\begin{pmatrix}
-y_A & x_A & 1 & 0 & p \\
-x_A & y_A & 0 & 1 & q \\
-y_B & x_B & 0 & 1 & t_x \\
-x_B & y_B & 0 & 1 & t_y \\
\end{pmatrix} \begin{pmatrix}
-x' \ \\
y' \\
\end{pmatrix} = \begin{pmatrix}
-x'NS \\
y'NS \\
\end{pmatrix},
\]

where \( p = r \sin \theta \) and \( q = r \cos \theta \). Inverting the matrix leads to the transformation parameters tx, ty, r, and θ, which we then apply to the position of the NS measured on the Chandra image to find its corrected position at that epoch,

\[
\begin{pmatrix}
-x'NS \\
y'NS \\
\end{pmatrix} = \begin{pmatrix}
-q & -p \\
p & q \\
\end{pmatrix} \begin{pmatrix}
-xNS \\
yNS \\
\end{pmatrix} + \begin{pmatrix}
t_x \\
t_y \\
\end{pmatrix}.
\]

The results of our transformation analysis indicate corrections to the nominal aspect that are small, but significant at the subarcsecond level. The stretch factors r required to scale from the original frame to the absolute one are 1.0022(6), 1.0033(3), and 1.0002(2) for data from the 1999 HRC-I, 2001 HRC-S, and 2005 epochs.
3.4. Uncertainty Estimate and a Simplification

The variance in $x'_n$ and $y'_n$ may be calculated by combining in quadrature the contributions from each of the 10 measured quantities, $x_A$, $y_A$, $x_B$, $y_B$, $x'_A$, $y'_A$, $x'_B$, $y'_B$, $x'_n$, and $y'_n$, by

$$\sigma^2_{x'_n} = \left(\frac{\partial x'_n}{\partial x_A}\right)^2 \sigma^2_{x_A} + \left(\frac{\partial x'_n}{\partial y_A}\right)^2 \sigma^2_{y_A} + \ldots + \left(\frac{\partial x'_n}{\partial y'_n}\right)^2 \sigma^2_{y'_n}. \tag{3}$$

For finding the magnitude of the proper motion, this tedious calculation can be considerably simplified by a very fortuitous accident: the NS position lies not far off the line joining stars A and B, and furthermore the direction of its motion is nearly parallel to this line. We can thus work in a coordinate system $(u, v)$ that is rotated by $30.5^\circ$ clockwise with respect to the $(x, y)$ system, so that the $u$-axis runs parallel to the line from B to A.\(^3\)

The original two-dimensional problem may then be approximated by a one-dimensional one: finding the position of an intermediate point along an elastic band that we allow to stretch uniformly between end points at known locations. Based on only five measured quantities, the $u$-coordinates for the three X-ray sources, which we denote as $a$, $b$, and $n$ for stars A, B, and the NS, respectively, and the corresponding optical coordinates for stars A and B, denoted as $a'$ and $b'$, we can calculate $n'$, the true position for the NS along the $u$-axis, along with its uncertainty $\sigma_{n'}$.

In this one-dimensional approximation, the transformation from the measured X-ray position $u$ at any epoch to the reference (optical) position is given simply by $u' = ru + t$, where $r$ is a stretch factor and $t$ a translation. Writing the transformation for the reference points $a$ and $b$, we immediately find

$$r = \frac{b' - a'}{b - a}, \quad t = a' - \frac{b' - a'}{b - a} a, \tag{4}$$

and thus $n'$ is

$$n' = a' + \frac{b' - a'}{b - a} (n - a). \tag{5}$$

In the usual manner for obtaining the variance in a quantity that depends on several independent variables,

$$\sigma^2_{n'} = \left(\frac{\partial n'}{\partial a}\right)^2 \sigma^2_{a} + \left(\frac{\partial n'}{\partial b}\right)^2 \sigma^2_{b} + \left(\frac{\partial n'}{\partial t}\right)^2 \sigma^2_{t} + \left(\frac{\partial n'}{\partial r}\right)^2 \sigma^2_{r}. \tag{6}$$

Straightforward calculation of the partial derivatives gives results such as

$$\frac{\partial n'}{\partial a} = \frac{(n - b)(b' - a')}{(b - a)^2} = r \frac{(n - b)}{(b - a)} \approx \frac{(n - b)}{(b - a)}, \tag{7}$$

where the final approximation uses the fact that the stretch factor $r$ is very nearly 1. With similar approximations for the other derivatives, equation (7) becomes

$$\sigma^2_{n'} \approx \left(\frac{n - b}{b - a}\right)^2 \sigma^2_{a} + \left(\frac{n - a}{b - a}\right)^2 \sigma^2_{b} + \sigma^2_{t} + \sigma^2_{r}. \tag{8}$$

\(^3\) While this line will be in slightly different directions at the different epochs, due to proper motions of A and B, we have used the orientation at the 2005 epoch for all. Proper motions of the reference stars lead to slightly different $(u, v)$ coordinates for each at the different epochs, but the contribution of differences in $r$ to the scale factor are negligible.
The individual uncertainties in Table 4 are calculated in this way and include the formal uncertainties in fits to the X-ray positions for stars A and B and for RX J0822−4300 and also the (smaller) position uncertainties from the UCAC2 catalog, for both epochs. We have included proper-motion uncertainties from the UCAC2, so the overall position uncertainty for the astrometric stars increases with time since the J2000.0 reference epoch. However, uncertainties in the X-ray source positions still dominate at all three epochs. Not surprisingly, the statistical uncertainties in all three proper-motion determinations are comparable. For our final result, we have taken a conservative approach: an unweighted average of the three measurements, with an uncertainty comparable to that of any of the individual ones and large enough to embrace them all.

3.5. Comparison with Hui & Becker (2006a)

In their analysis, HB06 have obtained a qualitatively similar but smaller and more uncertain value for the proper motion, \(0.104'' \pm 0.040''\ yr^{-1}\) at position angle \(240\deg\pm28\deg\). Their analysis differs from our own in several respects. (1) They used only the two HRC-I observations, while we have also included the 2001 observation with the HRC-S. (2) HB06 used only the closer of the two stars in the field (star A in our nomenclature; star B in theirs) as an astrometric reference, while we used both. (3) HB06 based their position fits on PSFs interpolated from the library in CALDB, while ours are based on PSFs we generated specifically for each source and observation using ChaRT and MARX. (The CIAO help text “Why use ChaRT instead of the PSF libraries?” explicitly discusses this difference.) (4) HB06 took the absolute position of their reference star from the 2MASS catalog, whereas we used the somewhat more precise ones from UCAC2 that also include proper-motion corrections. Despite these differences, the fact that independent analyses carried out by different groups lead to results that are qualitatively similar—the neutron star recoiling to the west-southwest with high velocity—further supports the robustness of the result. However, there are significant quantitative differences; HB06a found \(\mu = 0.104'' \pm 0.040''\ yr^{-1}\) versus our measurement of \(0.165'' \pm 0.025''\ yr^{-1}\). We discuss some implications of such a high proper motion and the implied transverse velocity in the next two sections.
Fig. 4.—Difference between the 1999 epoch (white events) and 2005 epoch (black events) HRC-I images, registered and scaled by the exposure time. The field is the same as in Figs. 1 and 2. The reference stars A and B largely disappear in the difference image, but RX J0822–4300 shows a noticeable displacement between the two epochs. This motion is more evident in the detailed view shown in the inset: (left) the 2005 epoch image alone, and (right) the difference image. The images are the same as those shown in Figs. 1 and 4, but the stretch has been changed to emphasize the narrow (<0.5") point-spread function. The circles in the inset are 12" in diameter, the same as in the full image and in Fig. 1. Proper motion toward the west-southwest is apparent, with a displacement roughly twice the width of the PSF.

to the stellar remnant; a neutron star space velocity exceeding \(\sim 100\) km s\(^{-1}\) cannot be produced by the break up of a binary system by a supernova.

Petre et al. (1996) predicted just this sort of motion for RX J0822–4300 based on its position 6° west-southwest of the expansion center for the oxygen knots measured by Winkler et al. (1988). For an age of 3700 yr, also determined by the knot kinematics, the expected transverse velocity is 980\(d_2\) km s\(^{-1}\). As shown in Figure 5, extrapolation backward from RX J0822–4300 along the vector representing the measured proper motion passes through the 90% confidence contour for the explosion center. The present measurement provides strong qualitative confirmation for the picture of a recoiling neutron star as laid out by Petre et al. (1996) but it appears that the actual velocity is \(\sim 50\%\) higher than they predicted. This suggests that the Puppis A remnant is somewhat younger than 3700 yr, and/or that the true expansion center is somewhat west and south of the one found by Winkler et al. (1988).

How asymmetric was the explosion? Given a velocity of 1570\(d_2\) km s\(^{-1}\) and a nominal neutron star mass of 1.4 \(M_\odot\), the kinetic energy associated with the compact star is \(\sim 3 \times 10^{53}\) ergs. This represents 3% of the total kinetic energy of \(10^{53}\) ergs produced by a canonical supernova explosion. Conservation of momentum requires that the net momentum of material ejected in the opposite direction is 1.4 \(M_\odot \times 1570\) km s\(^{-1}\) \(\sim 4 \times 10^{44}\) g cm s\(^{-1}\).

Overall, the Puppis A remnant looks reasonably symmetric in X-rays after the northeasterly gradient in the density of the ambient medium is taken into account. Any asymmetries associated with the forward shock have long been submerged by asymmetries in the interstellar medium. Oxygen is the most prominent ejecta species; the \textit{Einstein} FFPC detected a substantial overabundance of highly ionized oxygen at \(\sim 2 \times 10^6\) K. Assuming the oxygen is uniformly dispersed throughout the remnant, Canizares & Winkler (1981) estimated a total oxygen mass of \(>3 M_\odot\), from which they inferred a progenitor mass of \(>25 M_\odot\). Subsequent X-ray spectral imaging has not revealed any asymmetry in oxygen or any other ejecta species (Tamura et al. 1994). The only manifestation of asymmetry is the array of fast-moving knots, composed almost entirely of warm ([O iii]-emitting) oxygen and neon (Winkler & Kirshner 1985; Winkler et al. 1988).

It is possible to estimate whether sufficient mass is contained in these knots to balance the momentum. Winkler et al. (1988) gave 0.1 pc and 200 O atoms cm\(^{-3}\) as the typical knot size and density, for a mass \(\sim 0.04 M_\odot\). The proper motions for the 11 measured knots correspond to 1000–2500 km s\(^{-1}\) at 2 kpc. For a typical velocity component opposite the direction of the stellar remnant of \(1500\) km s\(^{-1}\), the corresponding momentum per knot is \(\sim 1.2 \times 10^{46}\) g cm s\(^{-1}\). Thus, \(\sim 30\) such knots are needed to offset the momentum of RX J0822–4300. Figure 5 suggests the existence of this number of knots is reasonable.

5. DISCUSSION

The nature of RX J0822–4300 is not well understood. Like most other objects lumped into the “central compact object” class, it is detected only in X-rays and shows no strong long- or short-term temporal variability. Hui & Becker (2006b) found a candidate period of \(\sim 0.22\) s, with a 5% ± 1% pulsed fraction.\(^4\) Its X-ray spectrum and flux are consistent with thermal emission from a neutron star surface. Pavlov et al. (2002) found acceptable fits using either a black body with \(kT \sim 0.4\) keV and an emitting radius \(R \sim 1.4\) km, or a hydrogen atmosphere model with \(kT_\text{eff} \sim 0.17\) keV; an emitting radius \(R_\text{sc} \sim 10\) km, and surface magnetic field strength \(B \sim 6 \times 10^{13}\) G; Hui & Becker (2006b) preferred a two black-body fit with temperatures and effective radii \(T_1 = 2.6 \times 10^8\) K, \(T_2 = 5.0 \times 10^8\) K, \(R_1 = 3.3\) km, and \(R_2 = 0.75\) km. Hui & Becker (2006b) placed an upper limit of \(2.9 \times 10^{-11}\) ergs cm\(^{-2}\) s\(^{-1}\) on the 0.5–10.0 keV X-ray flux from an associated wind nebula. An extremely stringent constraint has been placed on the radio luminosity of a wind nebula, 3 orders of magnitude below what would be expected if the stellar remnant were an energetic young pulsar (Gaensler et al. 2000). The resulting stringent radio limit on \(E\) suggests a high magnetic field (\(B > 6.4 \times 10^{13}\) G), which in turn invites comparison of this object with anomalous X-ray pulsars (AXPs) and soft gamma repeaters (SGRs). Such a comparison is premature, however, given the different spectral and temporal properties of RX J0822–4300. Velocity is not a discriminator, as AXPs and SGRs show a large range of inferred transverse velocities, from \(<500\) km s\(^{-1}\) to \(\sim 2900\) km s\(^{-1}\) (Gaensler 2000).

The object most similar to RX J0822–4300 is the central stellar remnant in Cas A. Cas A is thought to be the result of the core-collapse explosion of a comparably massive star (Willingale et al. 2003), with oxygen its most abundant nucleosynthesis product. Its stellar remnant has similar spectral properties to the one in Puppis A, although the one in Cas A is slightly hotter, as should be the case for a neutron star one-tenth the age (Pavlov et al. 2002). It too shows no evidence for either a wind nebula or strong temporal variability.\(^5\) Its transverse velocity is inferred to be \(330\) km s\(^{-1}\) for a distance of 3.4 kpc (Thorstensen et al. 2001), perpendicular to the most pronounced asymmetry axis in the remnant, defined by the “jet” and “counterjet” (Hwang et al. 2004).

The most challenging problem is to explain how neutron stars can have recoil velocities as high as we have measured for RX J0822–4300. Numerous mechanisms have been proposed to provide kicks to nascent neutron stars during a supernova explosion.

\(^4\) The 75 ms period once proposed for RX J0822–4300 has not withstood further scrutiny (Pavlov et al. 2002; Hui & Becker 2006b).

\(^5\) As for RX J0822–4300, the claimed periodicity of 12 ms of the Cas A source has not been confirmed (Murray et al. 2002).
Generally speaking, these fall into three broad categories: electromagnetically driven, neutrino/magnetic-field driven, and hydrodynamically driven. A review of the physics of each can be found in Lai (2001). Briefly, in the electromagnetically driven mechanism, radiation from an off-centered rotating magnetic dipole imparts a gradual acceleration to the neutron star along its spin axis. In the neutrino/magnetic-field driven mechanism, the kick is produced by asymmetric neutrino emission arising in a strong magnetic field. The hydrodynamically driven mechanism relies on asymmetric matter ejection resulting from hydrodynamic instabilities during the explosion. The first two mechanisms lead naturally to alignment of the kick direction close to the neutron star spin axis. Electromagnetically driven kicks can generate a spin-aligned kick of 1000 km s\(^{-1}\) but require millisecond spin periods to do so. Neutrino/magnetic-field driven kick models do not produce velocities higher than \(\sim 250\) km s\(^{-1}\) and require magnetic fields in excess of \(10^{15}\) G. Both these mechanisms seem unlikely candidates for the origin of RX J0822–4300.

Hydrodynamically driven shocks can in principle also provide kick velocities in excess of 1000 km s\(^{-1}\) and do not require spin-kick alignment. (Burrows & Hayes 1996; Burrows et al. 2006, 2007; Scheck et al. 2004, 2006). However, a spin-kick alignment can occur during a hydrodynamically driven kick if rotation is dynamically important for the core collapse and explosion (which in turn requires the initial spin period to be less than 1 ms). Alternatively, alignment can occur hydrodynamically from rotational averaging of the transverse momentum from small thrusts, provided the kick duration is substantially longer than the rotation period of the proto-neutron star (Spruit & Phinney 1998). Spin-kick alignment or near-alignment seems to be a common trait of isolated pulsars and neutron stars associated with pulsar-wind nebulae (Ng & Romani 2004; Johnston et al. 2005; Wang et al. 2006), but appears to be less common in neutron stars in binary systems (Wang et al. 2006).

Evidence regarding spin-kick alignment of RX J0822–4300 is mixed. The strongest supporting evidence is the existence of a bipolar cavity observed in H\(^\alpha\) centered on the star and oriented approximately along the direction of motion (Reynoso et al. 2003). These are postulated to arise from oppositely directed jets; they have swept out approximately 2 \(M_\odot\) of material. The absence of readily detectable pulsations argues against alignment: if the system were aligned, the apparent space-velocity vector, largely in the plane of the sky, provides an ideal viewing geometry for detecting pulsations. Alternatively, the marginal detection requires alignment not only of the spin and kick directions but also the magnetic field vector.

Independent of the spin-kick alignment question, the high transverse velocity of RX J0822–4300 together with its other properties challenge explosion models that produce neutron star kicks. The high magnetic field required for the electromagnetically driven mechanism is consistent with the absence of a wind nebula, but the absence of a period in the 6–12 s range typical of magnetars argues against such a mechanism. Electromagnetically driven kicks are generally viewed as unlikely because these require very fast (millisecond) spin periods, which are not associated with isolated pulsars. Kick mechanisms driven by neutrinos may be ruled out by the momentum balance between RX J0822–4300 and the oxygen knots, as well as by the high velocity. The presence of these knots, along with the lack of pulsations and the analogy with Cas A, all favor a nonaligned kick of hydrodynamic origin.

Recent SN explosion modeling by Burrows et al. (2007) makes two important predictions. This model posits a mechanism for core-collapse SNe relying on acoustic power generated in the inner core. The recoil mechanism is hydrodynamic, due either to acoustic power or an asymmetric neutrino flux. First, their model provides an estimate of the kick velocity: \(v_k \sim 1000 E/(10^{51}\text{ ergs})\) sin \(\alpha\) km s\(^{-1}\), where \(E\) represents the explosion energy, and sin \(\alpha\) parameterizes the anisotropy of the explosion. This expression predicts a correlation between explosion energy and neutron star recoil velocity. Even for the most extreme anisotropy, sin \(\alpha\) ~ 1, this model suggests that the explosion producing Puppis A must have been more energetic than the canonical \(10^{51}\) ergs and could have been considerably more so. It is currently thought that the explosion producing Cas A had energy \(2–4 \times 10^{51}\) ergs (Laming et al. 2006); thus, by analogy, a similar explosion energy might be expected for Puppis A. A higher explosion energy offers the benefit (for this model) of reducing the energy fraction that must be channeled into the kick.

A second prediction of the Burrows et al. (2007) model is that the proto-neutron star and a compensating amount of inner ejecta are expelled in opposite directions. The inner ejecta in core-collapse SNe are thought to be predominantly iron. The oxygen knots originate in an outer, hydrostatic burning layer, and move much more slowly than the initial velocity of material ejected from nearer the core. There is no evidence for excess Fe opposite the stellar direction of motion, however, or anywhere else in Puppis A. If fast Fe ejecta are present toward the east-northeast (up an ambient density gradient), one would expect these to become visible through interaction with the medium. The only apparent ejecta concentration is a region of enhanced Si to the north-northeast of RX J0822–4300, and not in line with its motion (Hwang et al. 2007). If the O knots are the only manifestation of an explosion asymmetry, it is not apparent how the momentum of the inner ejecta could be efficiently transferred to them.

6. CONCLUSIONS

As a summary, we may highlight the following points:

1. A precise position for RX J0822–4300, the presumed neutron star, has been measured from three independent Chandra...
HRC observations spread over a baseline of over 5 yr. Comparison among these yields a proper motion of $0.165'' \pm 0.025''$ yr$^{-1}$ at position angle $248^\circ \pm 14^\circ$. The uncertainty is dominated by the precision of position fits for two fiducial stellar X-ray sources used in the analysis.

2. This motion implies a transverse velocity of $(1570 \pm 240)$ (d/2 kpc) km s$^{-1}$ toward the west-southwest. This direction is roughly opposite to the motion of a handful of oxygen-rich optical filaments, presumably near-unindulited ejecta from the outer core of the progenitor, that are scattered throughout the northeast quadrant of Puppis A. Furthermore, backward extrapolation of the motion of RX J0822$-$4300 indicates an origin consistent with the measured expansion center for the O-rich filaments. This completes, in at least one SNR, what is becoming almost a canonical picture for core-collapse supernovae: an asymmetric supernova explosion accompanied by recoil of the compact stellar remnant, here almost surely a neutron star.

3. The kinetic energy associated with the transverse motion of RX J0822$-$4300 is $\sim 3 \times 10^{50}$ (d/2 kpc)$^2$ ergs, only about 3% of the total of $\sim 10^{51}$ ergs expected in a typical supernova. Some 2–3 dozen O-rich knots like those now glowing optically are sufficient to balance the momentum of the neutron star.

4. The physics of the explosion mechanism necessary to produce such a fast neutron star remains elusive, but the high kick velocity and lack of apparent pulsations from RX J0822$-$4300 do constrain possible models. Both these observations argue against neutrino/magnetic-field driven or electromagnetically driven mechanisms for the kick. The most likely candidate appears to be some mechanism through which hydrodynamic instabilities in the explosion lead to recoil of the compact remnant. However, the most specific such model, that of Burrows et al. (2007), is strained to explain both the high kick velocity and the apparent absence of iron-rich ejecta from the inner core of the Puppis A progenitor.

A complete kinematic study of Puppis A, including both the oxygen knots and the stellar remnant, will be interesting and should be carried out. CCD data should enable measurement of the motions for significantly more oxygen knots than the handful used by Winkler et al. (1988), who based their study on only 11 individual knots whose motions could be measured on photographic plates. A third-epoch Chandra observation with the HRC-I and/or HRC-S would further cement the kinematic picture.

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