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HIGH-RESOLUTION PARALLAX MEASUREMENTS OF SCORPIUS X-1

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ABSTRACT

The results of eight VLBA observations at 5 GHz, spanning 3 yr, have yielded a measured trigonometric parallax for Sco X-1 of $0\farcs00036 \pm 0\farcs00004$; hence, its distance is 2.8 ± 0.3 kpc. This is the most precise parallax measured to date. Although our measured distance is 40% farther away than previous estimates based on X-ray luminosity, our *Rossi X-Ray Timing Explorer* observations, with a measured luminosity of 2.3×10^{38} ergs s^{-1}, and determined distance continue to support the hypothesis that *Z*-source low-mass X-ray binary systems, like Sco X-1, radiate at the Eddington luminosity at a particular point in their X-ray color-color diagram.

Subject headings: astrometry — radio continuum: stars — stars: individual (Scorpius X-1) — techniques: interferometric — X-rays: stars

1. INTRODUCTION

Sco X-1 is a low-mass X-ray binary system and the brightest extrasolar celestial X-ray source. Sco X-1 is also one of six known "Z-type" X-ray quasi-periodic oscillators (Hasinger & van der Klis 1989) that have been suggested to radiate at or near the Eddington luminosity along the normal branch (Lamb 1989) or at the transition point between the normal and flaring branches in the X-ray color-color diagram (Vrtilek et al. 1991). These hypotheses combined with the measured X-ray flux density (Priedhorsky et al. 1986) suggested that the distance to Sco X-1 is about 2 kpc (Penninx 1989).

Bradshaw, Fomalont, & Geldzahler (1997, hereafter Paper I) determined a lower limit of 1300 pc (95% confidence) to Sco X-1, which placed it sufficiently distant for its X-ray luminosity to be near the Eddington limit for a 1.4 $M_\odot$ neutron star. Until the results of Paper I were obtained, a distance as small as 200 pc to Sco X-1 could not be excluded. With a more accurate distance, the understanding of the X-ray emission mechanism, the binary star masses, and the reliability of *Z*-type X-ray sources as standard candles can be enhanced. Thus, we have continued Very Long Baseline Interferometry (VLBI) observations using the Very Long Baseline Array (VLBA) to determine a more accurate distance. Although its radio emission is highly variable over periods of hours and days, we were able to determine the radio position of the binary system from the more complex structure of Sco X-1, yielding a significant improvement in the parallax measurement.

2. OBSERVATIONS

We undertook a series of eight VLBI observations of Sco X-1 between 1995 and 1998 (Table 1). During each of the 1995 and 1996 observing epochs, we used the 10 VLBA antennas for 2.1 hr and achieved a flux density rms sensitivity of about 0.07 mJy. The observations were made at 5 GHz with a 128 MHz bandwidth. The observations alternated between 4 minutes pointed at Sco X-1 and 1 minute pointed at the strong quasar 1504−166. All subsequent VLBA observations used the VLBA antennas plus one VLA antenna to provide for short spacings (St. Croix unavailable for epoch 1997.589 and VLA unavailable for epoch 1998.660). These latter observations pointed at Sco X-1 for 9 minutes and at 1504−166 for 1 minute with a total time on Sco X-1 of 3 hr. The data for Sco X-1 were correlated at two positions (epoch J2000): Sco X-1 (R.A. = $16^{\rm h}19^{\rm m}55\fs0850$, decl. = $-15°38'24\farcs9$) and the northeast source (Geldzahler et al. 1981; R.A. = $16^{\rm h}19^{\rm m}57\fs439$, decl. = $-15°37'24\farcs0$). The clock offsets and data quality were derived from observations of 1504−166, and the flux densities were determined from the system temperatures of the VLBA with an accuracy of 5%. The nominal angular resolution was 6×3 mas in a position angle of 0°. For the observations in 1997 and 1998, we included brief observations at 1.6 GHz to obtain spectral information on the source, but these lower resolution data were not used for the parallax analysis.

Calibration of the temporal phase changes for each antenna was determined by self-calibration on a radio source that is located only 70″ northeast (NE) of the binary and, hence, is in the primary beam of the antennas (Geldzahler et al. 1981). The fringe amplitude of the NE source at the longer VLBA baselines is 5.5 mJy and is detectable at all baselines in 4 minutes with a 128 MHz bandwidth. Images of the NE source for all VLBA observations showed slight resolution, but no significant flux density or structural variation. The total flux density is 8.9 mJy, which agrees with that measured from previous VLA observations at 5 GHz dating back to 1981. The phase calibrations from the NE source were applied to the data correlated at Sco X-1's position. The two objects are so close in the plane of the sky that the instrumental and atmospheric phase errors should be nearly identical for both sources. Images of Sco X-1 were then made with no further calibrations.

3. THE DETERMINATION OF THE RADIO CORE POSITION

A parallax of 0.23 ± 0.28 mas for Sco X-1 was determined from the first three VLBA observations in 1995 and 1996 (Paper I). During this period, Sco X-1 was in a low radio flux density state and little variability was detected. A radio core emission of 0.4 mJy was present for these three epochs, although the 1996.706 image contained two additional components well-separated from the radio core. As we discussed in Paper I, the motion of this 0.4 mJy radio component over the three epochs was consistent with a well-defined proper motion with virtually no parallax.

The strong radio flux density variability of Sco X-1 in the 1980's and early 1990's (Bradshaw, Geldzahler, & Fomalont

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TABLE 1
The Separation between the Northeast Source and Sco X-1

Date (MJD)	East-West Separation, X (arcsec)	North-South Separation, Y (arcsec)	Peak Core Flux Density (mJy beam^{-1})
1995.632/49950[a]	-34.06456 ± 0.00045	-60.9831 ± 0.0006	0.30
1996.126/50158[a]	-34.06701 ± 0.00015	-60.9889 ± 0.0005	0.57
1996.706/50342[a]	-34.07192 ± 0.00030	-60.9980 ± 0.0010	0.51
1997.589/50663:[b]			
02:05 UT	-34.07784 ± 0.00009	-61.0068 ± 0.0002	2.2
03:03 UT	-34.07784 ± 0.00008	-61.0065 ± 0.0002	2.6
04:20 UT	-34.07784 ± 0.00008	-61.0070 ± 0.0002	1.5
Weighted average	-34.07784 ± 0.00008	-61.0068 ± 0.0002	…
1997.638/50681:			
22:47 UT	-34.07799 ± 0.00008	-61.0064 ± 0.0002	3.9
23:52 UT	-34.07842 ± 0.00008	-61.0071 ± 0.0002	5.7
01:57 UT	-34.07813 ± 0.00005	-61.0071 ± 0.0001	3.5
02:15 UT	-34.07799 ± 0.00005	-61.0072 ± 0.0001	7.4
03:24 UT	-34.07842 ± 0.00015	-61.0078 ± 0.0003	3.6
Weighted average	-34.07814 ± 0.00008	-61.0071 ± 0.0002	…
1998.159/50871:[b]			
10:49 UT	-34.08102 ± 0.00009	-61.0136 ± 0.0002	6.8
11:56 UT	-34.08102 ± 0.00006	-61.0139 ± 0.0001	8.0
12:58 UT	-34.08088 ± 0.00006	-61.0135 ± 0.0001	7.6
14:15 UT	-34.08131 ± 0.00010	-61.0141 ± 0.0002	7.6
Weighted average	-34.08103 ± 0.00008	-61.0138 ± 0.0002	…
1998.162/50872:[b]			
10:49 UT	-34.08117 ± 0.00008	-61.0134 ± 0.0002	3.3
11:56 UT	-34.08102 ± 0.00008	-61.0134 ± 0.0001	3.6
Weighted average	-34.08109 ± 0.00008	-61.0134 ± 0.0001	…
1998.660/51054	-34.08521 ± 0.00030	-61.0199 ± 0.0006	0.5

[a] Revised position from Paper I.
[b] Some observations on this day not included because of poor (u-v) coverage, low core flux density, or blended core.

1997) was again observed after mid-1997. For the 1997.589 observation, the radio core was 1.8 mJy and there was additional, somewhat weaker emission present about 5 mas from the core. However, during the last four observations from 1997.638 to 1998.660, Sco X-1 was significantly variable in intensity and structure over periods as short as 10 minutes, so that normal imaging of the 3 hr of data produced distorted and smeared images of Sco X-1.

For the last four epochs, we routinely made images at 5 GHz at a variety of integration times: from 3 hr (the entire observation) to 21 individual 8 minute scans. Generally, when Sco X-1 was relatively weak (less than 5 mJy), variability and structure changes were slow. When Sco X-1 was in a radio flare state (greater than 20 mJy), structure variations over tens of minutes were observed. The radio structural properties of Sco X-1 will be discussed elsewhere (Geldzahler, Fomalont, & Bradshaw 1999). The relatively limited (u-v) coverage for these VLBA snapshots required careful deconvolution with the CLEAN algorithm to determine the radio structure. Sco X-1 was also sufficiently strong so that self-calibration of each of the short observations increased the image fidelity.

Even with the wealth of activity in Sco X-1, the radio core component was unambiguously identified most of the time for two reasons. (1) Because all of the images were phase-referenced to a nearby background radio source (which has shown no change in structure over the 4 years of VLBA observations and no variability over the 15 years of VLA and VLBA observations), all images are registered to within ~0.04 mas. The registration error, caused by receiver noise, is approximately equal to the east-west resolution (3 mas) divided by twice the ratio of the peak flux density to rms noise on the NE source image ($2 \times 5.5/0.15$). Systematic position errors caused by the 70″ separation of the NE source and Sco X-1 were estimated as follows: The typical error in registration of a VLBA image using a calibrator that is 2° away is about 2 mas (Beasley & Conway 1995). For a separation of 70″ (1/100 of 2°), any systematic error would decrease with calibrator-source separation, giving about 0.02 mas for this case—less than that due to noise in the images. (2) Since all images are tied to the same grid, once an approximate proper motion and parallax (or limit) was known for Sco X-1, we were able to anticipate with high confidence where the radio core should be on any image to within about 1 mas accuracy. This assumption is further strengthened if there is a component near this position and it is stationary (although changing in flux density), while other features appear to be moving. An example of a complex structure near the radio core is shown in Figure 1. Based on the relative motions of the components during the observation day and the a priori position of where the core should be from previous epochs (denoted by the X), we easily identify the middle component in Figure 1 as the radio core. Occasionally, the core component was severely blended with another component and a reliable position could not be measured. Such an example is shown in Figure 2. The expected core position (shown by the X) is located somewhere to the lower left of the large brightness centroid. However, in most of the images, the radio core was not significantly broadened.

We have assumed that the radio core, which is apparent on most images, is identified with the binary system. Since we occasionally see other radio components near the core, it is likely that what we are calling the radio core is composed of the emission from near the binary system plus other emission within about 2 mas (6 AU) of the binary system. However, since the residuals, for an individual determination, from the best-fit parallax and proper motion for the radio core are less than about 0.1 mas, we suggest that the radio emission from

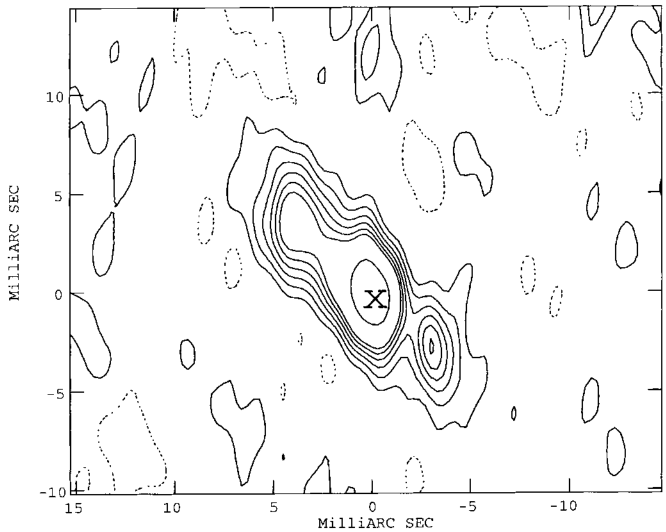

FIG. 1.—The 6 cm radio image of Sco X-1 on 1997.638 at 02:15 UT: contour levels are −0.3, 0.3, 0.6, 0.9, 1.2, 1.5, 1.8 3.6, 4.8, 14.4, and 28.8 mJy beam^{-1}. The X on the image marks the a priori core position.

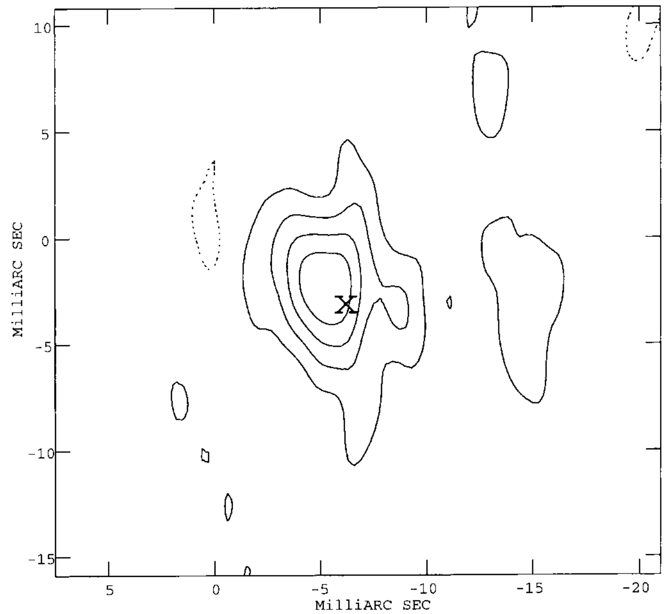

FIG. 2.—As in Fig. 1, but for 1998.162 at 13:05 UT. Contour levels are −0.2, 0.2, 0.4, 0.6, 0.8, 1.6, 3.2 6.4, 12.8, and 25.6 mJy beam^{-1}.

the core is generally within 1 AU of the core—and probably much closer. The binary system size is on the order of 0.3 AU (Cowley & Crampton 1975).

4. RESULTS

Table 1 shows the measured separation of the NE source from the radio core of Sco X-1 for all eight VLBA observations. For four of the epochs (1995.632, 1996.126, 1996.706, 1998.660) when the radio core was about 0.4 mJy and the structure was not very variable (less than 0.1 mJy), only one position is given for the day. The errors for these days are large because of the relatively low signal-to-noise ratio. For the other four days on which there were significant variability and structure changes, we have listed the separation as a function of time. Some of the variation over the day may be caused by internal structure in the radio core, but, as the table shows, it is at a level of 0.1 mas or less. For each observation, the peak core flux density is also given.

The separations (Sco X-1–NE source) for all epochs in Table 1 were fitted to five parameters: the zero levels of the east-west (X_0) and north-south (Y_0) positions at epoch 1996.2, the east-west (μ_x) and north-south (μ_y) proper motions, and the parallax (π). The best solution was obtained from a least-squares analysis of the data. Each datum was weighted by the standard deviation of its position determination. The weighted and unweighted fits were virtually identical with the weighted fit's uncertainty being slightly less. The best-fitting solution ($X_0 = -34''.06792 \pm 0''.00012$, $Y_0 = -60''.98997 \pm 0''.00027$, $\mu_x = -0''.00688 \pm 0''.00007$ yr^{-1}, $\mu_y = -0''.01202 \pm 0''.00016$ yr^{-1}, and $\pi = 0''.00036 \pm 0''.00004$) is consistent with, but a vast improvement over, our result in Paper I of $\pi = 0''.00023 \pm 0''.00028$.

Figure 3 (*top*) shows the measured east-west position of Sco X-1 after removal of the best-fit proper motion and position offset from the NE source. The positions and error bars are taken from Table 1. The dashed sinusoid shows the expected position change for a source with a parallax of 0.36 mas. It is clear that most of the parallax sensitivity is obtained when Sco X-1 is strong from the 1997.589, 1997.638, 1998.159, and 1998.162 observations. The two pairs of observations essentially sample two epochs separated by 6 months. The other four epochs, when Sco X-1 was weaker, do not add much to the parallax determination, but constrain the proper motion. The agreement in positions for the 1997.589 and 1997.638 epochs (18 days apart) and 1998.159 and 1998.162 (consecutive days) is evidence that the radio core position is stable to an accuracy less than 0.1 mas.

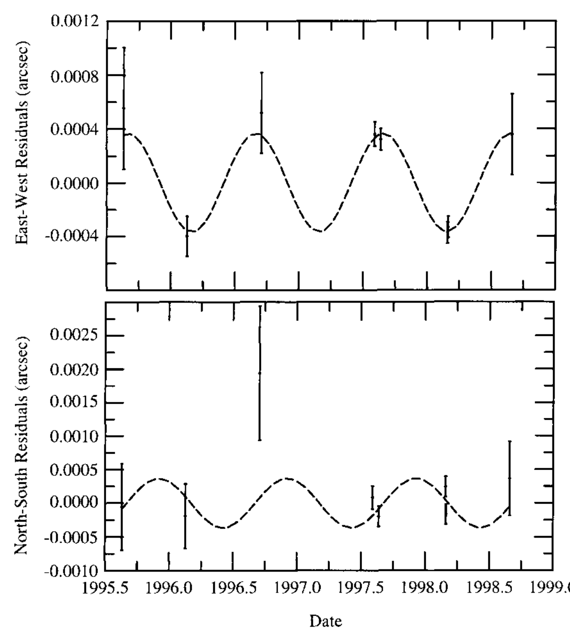

FIG. 3.—Sco X-1 6 cm east-west (*top*) and north-south (*bottom*) residual positions after removing proper motion. The data points are the weighted average from each VLBA observation date in Table 1. The error is mostly dependent on the core flux density. The sinusoid corresponds to the parallax of 0.36 mas.

The measured north-south position residuals of Sco X-1 are shown in Figure 3 (*bottom*). Again, the best-fit proper motion and offset are removed and the parallax is shown by a sinusoid. Since the observation dates are at times of small north-south parallax, the north-south data contains no parallax information. However, the data confirm the consistency of the radio core position to an accuracy of ∼0.3 mas.

5. DISCUSSION

Our observations were designed to determine the proper motion and parallax of Sco X-1. The initial results (Paper I), although of relatively low accuracy, were determined from simply interpretable images. However, our discovery of rapid radio structural variability in Sco X-1 for many of the more recent epochs posed a problem in imaging and determination of the radio core position. As we have shown, the radio core can be identified unambiguously in most instances. During these epochs the core was also a factor of 10 brighter in flux density, so that the positional accuracy is much greater than when the radio core was weak, although more stable. The resulting parallax is the most precise measured to date and is about an order of magnitude better than a typical *Hipparchos* (van Leeuwen & Evans 1998) determination.

Our measured parallax of Sco X-1, corresponding to a distance of 2.8 ± 0.3 kpc, places Sco X-1 40% farther away than prior distance estimates (2 kpc) based on the hypothesis of Eddington luminosity at the vertex of the X-ray color-color diagram's normal-flaring branch (Vrtilek et al. 1991). Thus, we were fortunate to have observed, with the *Rossi X-ray Timing Explorer* (*RXTE*), a normal-flaring branch transition of Sco X-1 during the 1997.162 observations, from which we derived a received X-ray flux of $\sim 2.4 \times 10^{-7}$ ergs s^{-1} cm^{-2} (2–20 keV) and an X-ray luminosity at 2.8 kpc of 2.3×10^{38} ergs s^{-1}. This X-ray flux is based on background– and dead-time–corrected spectra modeled with a multicomponent (photon absorption, blackbody, power-law, and Compton) spectrum model using the NASA/HEASARC XSPEC X-ray spectral fitting package. We estimate the derived flux accuracy to be approximately 3%. The previous Sco X-1 X-ray flux estimate ($\sim 3.3 \times 10^{-7}$ ergs s^{-1} cm^{-2}; Penninx 1989) differs because the Sco X-1 count rate was based on the average flux count in the normal branch instead of the count rate at the vertex between the normal and flaring branches. Our *RXTE* X-ray flux measured in the middle of Sco X-1's normal branch was 3.4×10^{-7} ergs s^{-1} cm^{-2}, consistent with the previous flux estimate.

For a distance to Sco X-1 of 2.8 kpc, our proper motion of 14.1 mas yr^{-1} gives a tangential velocity of 187 km s^{-1}. The radial velocity is -140 km s^{-1} (Cowley & Crampton 1975). These velocities correspond to a Galactic space velocity of 244 km s^{-1} ($U = 161$ km s^{-1}, $V = -77$ km s^{-1}, $W = 161$ km s^{-1})[4] relative to the local dynamic standard of rest. Sco X-1 is 1.1 kpc above the Galactic plane and inclined relative to the Galactic plane $\sim -64°$. It has a velocity ∼267 km s^{-1} less than Galactic escape velocity, assuming the distance to the Galactic center $R_0 = 8.7$ kpc (IAU, 1985). The distance, Galactic position, and space velocity suggests that Sco X-1 may be a halo object but makes less likely its association with Gould's Belt (Gould 1879), as discussed in Paper I.

6. CONCLUSIONS

The measured parallax of Sco X-1 derived from eight VLBA epochs is $0''.00036 \pm 0''.00004$, corresponding to a distance to Sco X-1 of 2.8 ± 0.3 kpc. This distance, which was derived from the most precise parallax measurement to date, and our *RXTE* observations at Sco X-1's X-ray normal-flaring branch vertex still support a model of Eddington luminosity for *Z*-sources at the normal-flaring branch vertex of the X-ray color-color diagram and enhances the possibility that these sources may be used as X-ray standard candles.

Finally, our results demonstrate that highly variable radio sources with a sufficient signal-to-noise ratio can be studied with the VLBA by making short time-sequence images, even though the (*u*-*v*) coverage is limited.

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[4] This result differs from that in Paper I because in Paper I there was a sign error in the calculation.

[5] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

REFERENCES

Beasley, A. J., & Conway, J. E. 1995, in ASP Conf. Ser. 82, Very Long Baseline Interferometry and the VLBA, ed. J. A. Zensus, P. J. Diamond, & P. J. Napier (San Francisco: ASP), 327
Bradshaw, C. F., Fomalont, E. B., & Geldzahler, B. J. 1997, ApJ, 484, L55 (Paper I)
Bradshaw, C. F., Geldzahler, B. J., & Fomalont, E. B. 1997, ApJ, 481, 489
Cowley, A., & Crampton, D. 1975, ApJ, 201, L65
Geldzahler, B. J., Corey, B. E., Fomalont, E. B., & Hilldrup, K. 1981, AJ, 86, 1036
Geldzahler, B. J., Fomalont, E. B., & Bradshaw, C. F. 1999, in preparation
Gould, B. A. 1879, Uranometria Argentina (Buenos Aires: Paul Emile Coni), 355
Hasinger, G., & van der Klis, M. 1989, A&A, 225, 79
Lamb, F. K. 1989, in Proc. 23d ESLAB Conference on X-Ray Astronomy, Vol. 1, ed. J. Hunt & B. Battrick (Paris: ESA), 215
Penninx, W. 1989, in Proc. 23d ESLAB Conference on X-Ray Astronomy, Vol. 1, ed. J. Hunt & B. Battrick (Paris: ESA), 185
Priedhorsky, W., Hasinger, G., Lewin, W. H. G., Middleditch, J., Parmar, A., Stella, L., & White, N. E. 1986, ApJ, 306, L91
van Leeuwen, F., & Evans, D. W. 1998, A&AS, 130, 157
Vrtilek, S. D., Penninx, W., Raymond, J. C., Verbunt, F., Hertz, P., Wood, K., Lewin, W. H. G., & Mitsuda, K. 1991, ApJ, 376, 278