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THE DISTANCE AND MILLIARCSECOND RADIO STRUCTURE OF SCORPIUS X-1

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ABSTRACT

From three VLBA observations at 5 GHz, taken over 13 months, we have measured the trigonometric parallax of Sco X-1 as 0″.00023 ± 0″.00028; hence, its distance is greater than 1300 pc. This supports the hypothesis that Sco X-1 radiates at or near the Eddington limit at the transition point between the normal and flaring branches of the X-ray color-color diagram. These results suggest that Sco X-1 and other Z-type quasi-periodic oscillators have a well defined luminosity and can be used as X-ray standard candles.

All three VLBA observations contain a radio core of flux density 0.5 mJy and size greater than 4 mas. However, the third VLBA observation revealed two additional radio components (separated by 12 mas and on opposite sides of the radio core) not present in the two previous observations. The evolution of these two components will remain unknown until multiepoch radio imaging and coordinated radio and X-ray total flux density measurements can be made.

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

1. INTRODUCTION

Sco X-1 is the brightest extrasolar X-ray source in the sky. It is a low-mass X-ray binary system with an orbital period of 0$^{\rm d}$.787 (Gottlieb, Wright, & Liller 1975; Cowley & Crampton 1975). Its distance is unknown because the normal star's spectral luminosity class is corrupted by the presence of the hot X-ray source.

Sco X-1 is one of six known Z-type X-ray quasi-periodic oscillator (QPO) sources (Hasinger & van der Klis 1989). Van Paradijs, Penninx, & Lewin (1988) and Penninx (1989) suggested that Z-sources radiate at or near the Eddington luminosity at the transition point between the normal and flaring branches in the X-ray color-color diagram. An accurate distance measurement to at least one of these QPOs is required to test this hypothesis.

Precise astrometric measurements with the Very Large Array (VLA) spanning 10 yr showed Sco X-1's proper motion to be 13.3 mas yr^{-1} (Fomalont & Geldzahler 1991). We have extended and augmented our radio studies with the Very Long Base Array (VLBA) to determine the distance to Sco X-1 and its radio structure, which is unresolved at 1″ resolution.

2. OBSERVATIONS

We used the VLBA for three epochs that spanned 13 months. All 10 VLBA antennas were used for 2.4 hr, and they achieved a flux density sensitivity of about 0.07 mJy. The observations were made at 5 GHz with a 256 MHz bandwidth. The observations alternated between 4 minutes pointed at Sco X-1 and 1 minute pointed at the strong quasar 1504−166. 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$^{\rm s}$.0850, decl. = −15°38′24″.9) and the northeast source (R.A. = 16$^{\rm h}$19$^{\rm m}$57$^{\rm s}$.4390, decl. = −15°37′24″.0). The clock offsets and data quality were derived from observations of 1504−166, and the flux densities were tied to the system temperatures of the VLBA with an accuracy of 5%. The nominal angular resolution was 15 × 4 mas in a position angle of 0°. Structures larger than about 50 mas were fully resolved.

After the initial clock calibration from 1504−166, the data correlated at the position of the northeast source were imaged using the standard phase self-calibration techniques in the Astronomical Image Processing System. The peak flux density of the northeast source was 4.1 ± 0.08 mJy, and the integrated flux density was 9.8 ± 0.17 mJy. The integrated value, as measured by the VLBA, was close to that observed with all previous VLA observations; hence, it has not varied significantly over the 15 yr period.

The temporal phase changes for each antenna, which were determined from the self-calibration of the northeast source, were applied to the data that were correlated at the Sco X-1 position. Since the two sources were observed simultaneously and are only ≈70″ apart, the instrumental and atmospheric phase errors for each should be virtually identical. From the noise-limited images of Sco X-1 made from the northeast source phase calibration, the accurate position of the Sco X-1 components were determined using a Gaussian-fitting routine on the CLEANed image. At a time near the end of our third VLBA epoch, we obtained 10 minutes of phased VLA data at 4.9 GHz and measured the total flux density of the northeast source (9.8 ± 0.2 mJy) and of Sco X-1 (3.5 ± 0.2 mJy).

3. RESULTS

The measured separation for all VLA, previous VLBI, and current VLBA observations between the northeast source and Sco X-1 are provided in Table 1. All data were transferred to the J2000 ephemeris, and the estimated error in the conversion of the VLA B1950 epoch observations is less than 2 mas for the position difference. The estimated errors were based on the sum of the image rms noise and Gaussian fit error. The last three entries (epoch 1996.706) give the positions for the three components of Sco X-1. The map for this epoch's data is shown in Figure 1. The locations of the components detected

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TABLE 1

THE SEPARATION BETWEEN THE NORTHEAST SOURCE AND SCO X-1

Date	E-W Separation X (arcsec)	N-S Separation Y (arcsec)	Array
1981.098	33.9757 ± 0.007	60.8002 ± 0.009	VLA
1982.212	33.9527 ± 0.008	60.7941 ± 0.01	VLA
1983.910	33.9466 ± 0.011	60.8151 ± 0.013	VLA
1984.964	33.9845 ± 0.004	60.8383 ± 0.004	VLA
1985.183	33.9795 ± 0.006	60.8382 ± 0.008	VLA
1987.251	34.0046 ± 0.0013	60.8760 ± 0.0022	US-VLBI
1988.430	34.0075 ± 0.001	60.8844 ± 0.0016	EVN
1990.345	34.0223 ± 0.004	60.8984 ± 0.005	VLA
1991.460	34.0322 ± 0.001	60.9256 ± 0.0016	EVN
1995.632	34.0637 ± 0.0005	60.9814 ± 0.001	VLBA
1996.126	34.0681 ± 0.0003	60.9885 ± 0.0005	VLBA
1996.706	34.0722 ± 0.0005	60.9954 ± 0.001	VLBA-core
	34.0667 ± 0.0004	60.9909 ± 0.0008	VLBA-NE
	34.0756 ± 0.0002	60.9975 ± 0.0003	VLBA-SW

in the two previous VLBA epochs are also shown in Figure 1; the ellipse sizes indicate the rms position error.

In 1995.632, Sco X-1 consisted of one component with a peak flux density of 0.35 ± 0.08 mJy. It may be slightly resolved, but the signal-to-noise ratio is too low to assume anything other than a point source. In 1996.126, the component had a peak flux density of 0.45 ± 0.08 mJy and again was consistent with an unresolved component ($\theta \leq 4$ mas). Previous VLA observations (Bradshaw, Geldzahler, & Fomalont 1997) showed that the typical 5 GHz flux density of Sco X-1 varies between 4 and 10 mJy, although it does have quiescent periods of flux density less than 1.0 mJy. Thus, the low flux density for the first two VLBA epochs represents the quiescent phase of the binary.

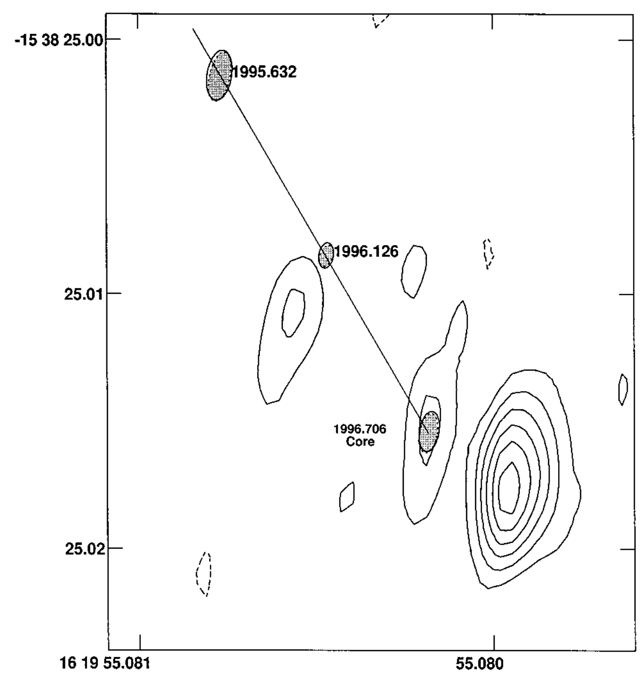

FIG. 1.—1996.706 Sco X-1 radio image superposed with the Sco X-1 positions during the previous two epochs. Proper motion is not removed: contour levels are −0.2, 0.2, 0.4, 0.6, 0.8, 1.0, and 1.2 mJy beam^{-1}. The binary cores are shaded, and the proper motion line is illustrated. The coordinate labels are the northeast source minus the Sco X-1 positions.

The structure of the 1996.706 epoch VLBA observation differs markedly from that of earlier epochs in that three distinct components are present. Figure 1 shows (and the subsequent parallax analyses leave little doubt) that the central component is the same object that was seen in the previous two epochs. First, the peak flux density is 0.44 ± 0.08 mJy, in good agreement with the previous epochs. Second, its position is consistent with the known proper motion of Sco X-1, based on 15 yr of data, and virtually no parallax exists among the three VLBA observations. There is no reasonable parallax and proper-motion solution in which either of the other two components in the last epoch could be identified with the one component seen earlier. Thus, the middle component is probably associated with the radio binary system, and we will designate this component as the *radio core.*

The southwest component in the 1996.706 epoch is separated from the radio core by 4.0 ± 1.2 mas, with a peak flux density of 1.4 ± 0.1 mJy, an integrated flux density of 2.8 ± 0.3 mJy, and a size of ~2.5 mas. The northeast component is separated from the radio core by 7.2 ± 1.9 mas with a peak flux density of about 0.45 ± 0.08 mJy. The sum of the flux densities of Sco X-1's milliarcsecond components (3.7 mJy) is in excellent agreement with the total flux density as measured simultaneously with the VLA (3.5 ± 0.2 mJy). Hence, *there is no missing flux density and no missing large structure for Sco X-1 in the VLBA image.*

4. DISCUSSION

The purpose of our observations was to obtain high-precision position estimates for an accurate parallax measurement of Sco X-1. The serendipitous triple structure results from the third VLBA epoch, however, provide insight into the dynamics and evolution of the binary system.

The position data for the radio core were fitted to five parameters: the zero level of the east-west (x) and north-south (y) positions, the east-west (μ_x) and north-south (μ_y) proper motions, and the parallax (π). The 1996.706 epoch VLBA observation suggests that, unless VLBI images of Sco X-1 are made, the measured centroid of the source could be offset from the radio/binary core by several milliarcseconds. Therefore, only the three VLBA observations were used to determine the parallax. Positional uncertainty is present in all previous VLBI and VLA observations, but it should average out so that the proper motion derived from these observations over more than 10 yr is still very accurate. The best solution was obtained by a least-squares analysis of the data. The best-fit χ^2 was as expected from the number of degrees of freedom and indicated that the estimated errors cited in Table 1 were realistic. The parameter errors, including the contribution from the correlation among the parameters, were determined from a normal χ^2 analysis.

The best-fitting solution using the errors in Table 1 ($x = 34''.0684 \pm 0''.0.0016$, $y = 60''.9892 \pm 0''.0008$; $\mu_x = 0''.0079 \pm 0''.0005$ yr^{-1}, $\mu_y = 0''.0129 \pm 0''.0006$ yr^{-1}; total proper motion $\mu_t = 0''.0151 \pm 0''.0008$ yr^{-1}, $\pi = 0''.00023 \pm 0''.00028$) is consistent with optical measurements (Sophia, Eichhorn, & Gatewood 1969; van Altena 1972) of $\mu_t = 0''.021 \pm 0''.003$ yr^{-1} and $\pi = 0''.001 \pm 0''.006$. All errors are one standard deviation.

With a parallax of 0.23 ± 0.28 mas, there is an 84% chance that the parallax is less than 0.51 mas (or the distance is greater than ~2 kpc) and a 95% chance that the distance is greater than 0.79 mas (or ~1.3 kpc).

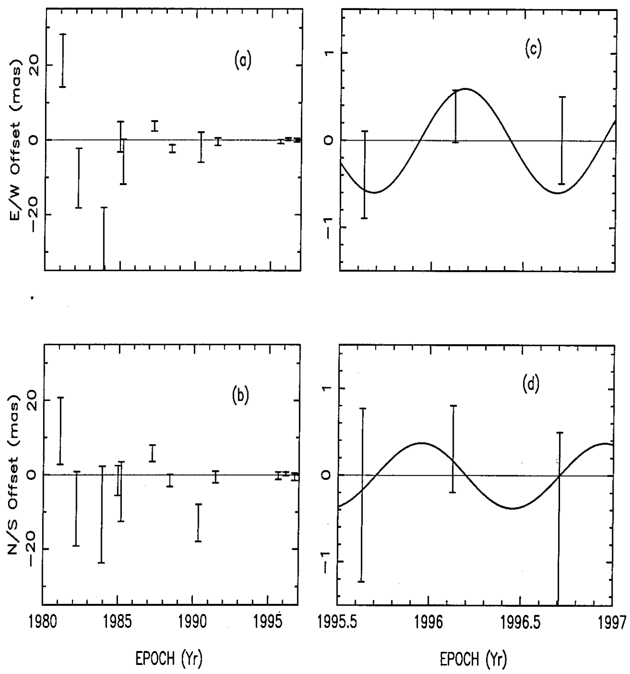

FIG. 2.—Residual data after best fit for the northeast-Sco X-1 positions: (*a*) east-west, (*b*) north-south residuals for all observations after removing the best-fit proper motion. (*c*) East-west, (*d*) north-south residuals for the three VLBA observations after removing the best-fit proper motion. The right scale is 20 times the left, and the sinusoid corresponds to a Sco X-1 parallax of 0.6 mas.

Figures 2*a* and 2*b* show the residual fit of the east-west and north-south data, respectively, of the 12 observations between 1981 and 1996. The line at zero corresponds to the removal of the best-fitting intercept and proper motion. Both the east-west and north-south data over the 16 yr of observation are consistent with a simple separation intercept and a linear proper-motion slope to a level of ∼1 mas.

The 15.1 ± 0.8 mas yr^{-1} proper motion and the -140 km s^{-1} radial velocity of Sco X-1 (Cowley & Crampton 1975) corresponds to a Galactic space velocity of 169 km s^{-1} ($U = 45$ km s^{-1}, $W = -83$ km s^{-1}, $V = -140$ km s^{-1}) at $d = 1.3$ kpc. Sco X-1's Galactic orbit is prograde, inclined relative to the Galactic disk, and ∼100–150 km s^{-1} less than the Galactic escape velocity. The peculiar transverse velocity is ∼38 km s^{-1} relative to the local standard of rest. This could indicate that Sco X-1 is a halo object or is associated with an expanding group such as Gould's Belt.

Figures 2*c* and 2*d* show the residual fit of the east-west and north-south VLBA data, respectively. The line corresponds to zero parallax, and the sinusoidal-shaped line corresponds to a 0.6 mas parallax, or a distance of 1.33 kpc. The parallax solution is dominated by the higher angular resolution of the east-west data and the chosen epochs that maximized the east-west parallax angle. The north-south data show the consistency of the data to the fit and that the estimated error bars are reasonable.

Our determination of a distance greater than 1.3 kpc demonstrates that Sco X-1 is not a member of the Sco-Cen association (Sofia et al. 1969). The result supports the model (Hasinger 1987; Lamb 1989; van der Klis 1989; Vrtilek et al. 1991; van der Klis et al. 1996) in which Sco X-1 and the other Z-sources radiate at the Eddington luminosity at the vertex of the normal and flaring branches of the X-ray color-color diagram. The luminosity is relatively insensitive to the mass of the compact object, which is $\sim 1.0\,M_\odot$. Sco X-1's distance must be close to 2 kpc for the observed X-ray flare flux density to be equal to the predicted model X-ray flare luminosity (Penninx 1989). This value is in good agreement with our distance measurement.

The six known Z-type binaries have remarkably similar observed characteristics and appear to have $\sim 1\,M_\odot$ compact objects as the primaries (Penninx 1989). Thus, determining Sco X-1's distance is an important first step in defining Z-sources as the first X-ray standard candle.

Since neutron stars such as Sco X-1 are thought to be created in Type II supernovae involving B-type stars, we also note that Sco X-1 is in the general direction of the Gould Belt (Gould 1879), which is a spur of the local spiral arm. The distance to the B-type stars constituting the Belt is roughly 1.5–2.5 kpc. Further refinement of the measurement of the distance to Sco X-1 will help us determine if any specific relationships between the binary and Gould's Belt exist.

The third VLBA epoch image shows that radio components were formed in the intervening 6 months after the second epoch. Because the core is symmetrically located between the components, it is presumed that the components were ejected from Sco X-1. Mass transfer has been surmised for years, but this is the first real evidence that such ejection does occur. However, until multiepoch observations are obtained and component velocities are measured, we could alternatively say that the components are stationary and simply come and go. Although it may be premature to extrapolate these results before such additional data are obtained, we hope the following discussion is useful and anticipates some of the future results:

1. In our third VLBA epoch, we have identified the radio core as the central component and have suggested that it is relatively stable. This implies that, when the total emission of Sco X-1 is greater than about 0.5 mJy, the additional emission is associated with ejecta, which are perhaps often similar to the two outer components in Figure 1. The limited flux density monitoring of Sco X-1 (Hjellming et al. 1990; Bradshaw et al. 1997) shows that the source is in an excited state over 85% of the time. In fact, the flux density of Sco X-1 can vary from 4 mJy to over 20 mJy in a matter of hours (Bradshaw et al. 1997). The correlation of these radio flares with any extended (or unresolved) Sco X-1 emission is unknown, but it is important for understanding the evolution of the binary system. Any correlation with X-ray variations is also important.

2. The simple model of equal and opposite moving material being simultaneously ejected with relativistic velocities from the radio core is incompatible with the relative flux density of the outer components compared with their relative distance from the core. Doppler effects alone cannot produce the configuration seen in Figure 1. All we know about the two radio components is that they are younger than 6 months old and probably older than 4 hr. A lower limit age in the strongest component would have smeared the image over the 2.4 hour observations and produced unCLEANable sidelobes, which were not present on the image. We cannot even say that these components are moving. Several multiepoch observations should determine if the ejecta are produced simultaneously on each side of the radio core or are separate events. The

constancy of the angle of ejection is also an important parameter to be determined.

3. Assuming a distance to Sco X-1 of 2 kpc and an inclination angle to the line of sight of 25° (Cowley & Crampton 1975), the distances of the southwest and northeast sources from the radio core are 19 and 33 AU, respectively. The large distance of the components from the binary system, which is much greater than 1 AU, argues strongly that the components are moving out from the binary.

However, the components could be produced by an intermittent, invisible (i.e., highly efficient) beam of particles from the binary colliding with two clouds that are 19 and 33 AU from the binary.

4. Comparison with Cyg X-3, which has a separation speed of $0.35c$ (Geldzahler et al. 1983), and SS 433, which has a separation speed of $0.26c$, (Abell & Margon 1979) is interesting. If $0.3c$ is also the typical velocity of the components of Sco X-1, then both components are about 10 hr old. This is not excluded from this one epoch of data. At these speeds, the components probably become fully resolved in less than about 100 hr (4 days).

5. CONCLUSIONS

The measured parallax of Sco X-1, derived from three VLBA epochs, is $0\overset{''}{.}00023 \pm 0\overset{''}{.}00028$. It is very likely that the distance to Sco X-1 is greater than 1.3 kpc distant and, thus, supports a model of Eddington luminosity for Z-sources at the normal branch-flaring branch vertex of the X-ray color-color diagram.

The VLBA images suggest that there is a quasi-quiescent radio core of about 0.5 mJy that has persisted over 13 months (and probably much longer). However, two radio components are present in the third VLBA epoch but not in the first two VLBA observations. The speeds and ages of the components are unknown at the present time. They are older than ~4 hr, but younger than ~6 months.

Multifrequency VLBA observations are required to (1) reduce the uncertainties in the distance measurement, (2) determine the structural and temporal evolution of the Sco X-1 radio components, and (3) determine the correlation, if any, between the radio and X-ray light curves and with the structural changes. This further study will doubtless increase our knowledge of the dynamics and energetics of this, the brightest of extrasolar system X-ray sources.

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