

SCORPIUS X-1: AN EVOLVING DOUBLE RADIO SOURCE

B. J. GELDZAHLER

Applied Research Corporation

AND

E. B. FOMALONT

National Radio Astronomy Observatory¹

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ABSTRACT

The radio emission from Sco X-1 has been monitored with the VLA over a 5 yr period with 0".4 resolution at 4.85 GHz. The source contains three components: an unresolved ($<0".1$) radio core coincident with the stellar binary system; an unresolved lobe, $\sim 1'$ northeast of the core; and an extended (10") lobe, $\sim 1'$ southwest of the core. All radio components are approximately comoving with the binary system ($0".030 \text{ yr}^{-1}$) and are thus undoubtedly associated with it. The northeast lobe is moving away from the core at a rate of $0".015 \pm 0".002 \text{ yr}^{-1}$, which corresponds to a velocity of $36 \pm 5 \text{ km s}^{-1}$, assuming a distance of 500 pc to Sco X-1. The relative velocity of a hot spot in the southwest lobe with respect to the core is less than 70 km s^{-1} . The flux density in the lobes appears to vary by $\sim 20\%$ over time scales of 1 yr, and the variations between the lobes may be correlated.

The twin-exhaust beam model where energy is transported from the core to the lobes in narrow beams is the most acceptable model for the evolution of the source. However, a surprisingly high interstellar density ($>0.6 \text{ cm}^{-3}$) is needed to restrain the velocity of the northeast lobe (presumably the working surface of the beam). The relatively rapid flux density variations, especially for the extended southwest lobe and the small linear size of the working surfaces indicate radiative lifetimes of the relativistic electrons which are much shorter than those calculated from equipartition calculation. We suggest a magnetic field strength of 0.1 G in the hot spots and the possibility of partially coherent radiation processes to explain the flux density variations.

Subject headings: stars: individual — stars: radio radiation — X-rays: binaries

I. INTRODUCTION

The X-ray binary star system Sco X-1 is the only known Galactic object to exhibit a radio morphology similar to the classical extragalactic double radio sources. It has been suggested that the process of forming the lobes in Sco X-1 is similar to that in the luminous extragalactic sources, and appropriate scaling laws have been surmised (see, e.g., Begelman, Blandford, and Rees 1984). It may be through Galactic objects such as Sco X-1 and SS 433, with their relatively short characteristic time scales for structural and intensity variations, that insight can be gained into the physical phenomena operating in double radio sources.

Observations of Sco X-1 were made at the VLA in the A-configuration at six epochs between 1980 and 1985. The results from the 1980 observations were reported in Geldzahler *et al.* (1981; hereafter called Paper I) and clearly showed the triple morphology of Sco X-1. Further observations in 1981 and 1982 (Fomalont *et al.* 1983; hereafter called Paper II) provided interesting upper limits to the rate of separation of the northeast lobe from the radio core. Using the conventional beam model (Blandford and Rees 1974), it is difficult to reconcile the large beam energy flux needed to supply the radio energy to the lobes with a low beam momentum flux which is consistent with the slow rate of lobe separation.

We, therefore, continued the monitoring of the radio emission from Sco X-1. In this paper we report on the accurate determination of the proper motion of the northeast lobe and

the radio core and on flux density variations within the lobes. The understanding of these phenomena in terms of the conventional beam model is still difficult.

II. OBSERVATIONS AND DATA REDUCTIONS

All of the observation sets with appropriate parameters are listed in Table 1. Although most of the sets were observed at 1.5 GHz as well as 4.85 GHz, we report only on the 4.85 GHz observations in this paper. The five observation sets in the full A-configuration at the VLA are the most important for establishing the proper motion and variability. For the observations after 1982, two independent frequency channels were used, each of 25 MHz bandwidth in order to minimize "bandwidth" smearing of the outer components in the A-configuration. The rms noise estimates are based on the quality of the output images and are somewhat larger than expected values from the system parameters. Because the 1980 observation set was made with the uncompleted VLA, it was not suitable for detailed comparison of component positions with the later epochs and will not be relied on heavily. The low-resolution observations in the D-configuration in 1984 were useful in checking the integrated flux densities of the extended components. The positional accuracy for these data are too low to be useful for proper-motion studies.

The calibration of the data was outlined in Paper I. The flux density scale at all epochs was tied to the calibrator source 3C 286 to an accuracy of 1%. This calibrator has no history of flux density variations at a level of 4% over 5 yr. The position of Sco X-1 was tied to the assumed position of the calibrators 1555+001 and 1504-167 to an rms accuracy of 0".02 at each

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TABLE 1
OBSERVATIONS OF SCO X-1 AT 4.85 GHz

Observation Date	Epoch (yr)	Integration Time (hr)	Frequency (GHz)	Bandwidth (MHz)	Frequency (GHz)	Bandwidth (MHz)	rms Noise (mJy)	Configuration
1980 Feb 09	1980.110	4.1	4.885	50	...	...	0.13	Partial A
1981 Feb 04	1981.098	4.1	4.873	25	...	...	0.056	Full A
1982 Mar 18 ...	1982.212	3.2	4.873	25	...	...	0.072	Full A
1983 Nov 27 ...	1983.910	7.2	4.873	25	4.823	25	0.043	Full A
1984 Sep 16	1984.712	5.1	4.885	50	4.835	50	0.070	Full D
1984 Dec 16 ...	1984.964	5.7	4.873	25	4.823	25	0.051	Full A
1985 Mar 07 ...	1985.183	6.7	4.873	25	4.823	25	0.033	Full A

NOTE.—Flux density calibrators: 3C 286, 7.41 Jy at 4.88 GHz, 7.47 Jy at 4.82 GHz.
Position calibrators: 1555+001, R.A. = $15^{\text{h}}55^{\text{m}}17^{\text{s}}.688$, decl. = $+00^{\circ}06'43''.54$. FK 4 epoch (1950): 1504–167, R.A. = $15^{\text{h}}04^{\text{m}}16^{\text{s}}.430$, decl. = $-16^{\circ}40'59''.60$.

epoch by alternating observations between Sco X-1 and the calibrators in a 20 min cycle. This accuracy corresponds to a phase error of $\sim 20^{\circ}$ at the longest baseline. The absolute positional accuracy with respect to the FK 4 reference frame of the calibrators is $0''.08$ in each coordinate (Fomalont and Perley 1983).

Radio images were made at each epoch with the identical software using the the standard mapping, cleaning, and self-calibration algorithms in AIPS. For the 1983, 1984, and 1985 the observations at each frequency were reduced separately. Only one iteration of phase self-calibration was necessary to correct for the tropospheric phase fluctuations in order to reach the expected signal-to-noise level. For the 1981, 1984, and 1985 observations, the radio core varied significantly over the 10 hr observation period resulting in large sidelobes emanating from the core in the radio image. These were removed by splitting the observations into four or five parts, during which the core varied insignificantly, mapping and cleaning each part separately, and then recombining the images. Finally, the two 25 MHz channels, separated by 50 MHz, for the 1983, 1984, and 1985 observations were combined to obtain a radio image at the average frequency. The synthesized apertures were virtually identical for the five epochs, and best-quality radio images were made with $0''.5$ N/S by $0''.4$ E/W resolution and with $3''.0$ resolution.

The gross features of Sco X-1 are shown with $3''$ resolution in Figure 1. The central component (radio core) is nearly coincident with the X-ray binary system. It is unresolved ($<0''.1$) and variable (<1 to >20 mJy) over time scales as short as 1 hr. The NE lobe has a flux density of ~ 9 mJy and is also unresolved ($<0''.1$). The southern "lobe" contains two emission regions separated by $\sim 10''$, with an integrated flux density of 5

mJy. An $0''.5 \times 0''.4$ resolution image of the lobe is shown in Figure 2. The outer edge contains an unresolved hot spot ($<0''.15$) with a flux density of ~ 0.5 mJy; the remaining emission shows no other bright regions. For subsequent analysis of the SW hot spot the radio image was convolved with a high-pass filter which passed data with spacing greater than 6 km and suppressed all of the large-scale structure in the SW lobe.

Papers I and II suggested that the likelihood the NE and SW lobes are unrelated background sources is very small based on circumstantial evidence concerning the morphology of the source and the proximity of the components to the core. In this paper we show that all three components are moving with respect to the background quasar calibrators and that they generally share the same proper motion; this is conclusive evidence concerning their association. No obvious optical identification underlies either the northern lobe or the southern hot spot.

III. RESULTS

a) The Motion of the Components

The positions of the core and the NE lobe were measured from the $0''.5 \times 0''.4$ image. For the SW hot spot we used the high-pass filtered $0''.5 \times 0''.4$ image in which the extended structure was suppressed. The intensity distributions in the vicinity of each component were fitted to an elliptical Gaussian-shaped component in order to determine the peak flux density, the integrated flux density, the right ascension, the declination, the major axis, minor axes, and orientation of the ellipse. An average zero level was also determined in the fit. These results are shown in Table 2. The error estimate, E , of the fits were

TABLE 2
POSITIONS OF COMPONENTS OF SCO X-1

EPOCH (yr)	CORE		NE LOBE		SW HOT SPOT	
	Right Ascension ($16^{\text{h}}17^{\text{m}}$)	Declination (-15°)	Right Ascension ($16^{\text{h}}17^{\text{m}}$)	Declination (-15°)	Right Ascension ($16^{\text{h}}17^{\text{m}}$)	Declination (-15°)
1980.108	$04^{\text{h}}45^{\text{m}} \pm 0^{\text{s}}.010$	$31^{\circ}15'25'' \pm 0''.07$	$06^{\text{h}}24^{\text{m}} \pm 0^{\text{s}}.01$	$30^{\circ}14'66'' \pm 0''.07$	...	...
1981.098	$04^{\text{h}}46^{\text{m}}4 \pm 0.0015$	$31^{\circ}15.146 \pm 0.020$	$06^{\text{h}}36^{\text{m}}2 \pm 0.0015$	$30^{\circ}14.504 \pm 0.020$	$01^{\text{h}}90^{\text{m}}43 \pm 0^{\text{s}}.0050$	$32^{\circ}33'988'' \pm 0''.059$
1982.212	$04^{\text{h}}46^{\text{m}}42 \pm 0.0015$	$31^{\circ}15.182 \pm 0.020$	$06^{\text{h}}33^{\text{m}}19 \pm 0.0015$	$30^{\circ}14.542 \pm 0.020$	$01^{\text{h}}90^{\text{m}}46 \pm 0.0037$	$32^{\circ}33.846 \pm 0.046$
1983.910	$04^{\text{h}}46^{\text{m}}16 \pm 0.0018$	$31^{\circ}15.216 \pm 0.027$	$06^{\text{h}}33^{\text{m}}20 \pm 0.0015$	$30^{\circ}14.558 \pm 0.020$	$01^{\text{h}}90^{\text{m}}33 \pm 0.0025$	$32^{\circ}33.902 \pm 0.033$
1984.964	$04^{\text{h}}46^{\text{m}}44 \pm 0.0015$	$31^{\circ}15.288 \pm 0.020$	$06^{\text{h}}34^{\text{m}}8 \pm 0.0015$	$30^{\circ}14.600 \pm 0.020$	$01^{\text{h}}90^{\text{m}}73 \pm 0.0022$	$32^{\circ}33.938 \pm 0.025$
1985.183	$04^{\text{h}}46^{\text{m}}64 \pm 0.0017$	$31^{\circ}15.282 \pm 0.024$	$06^{\text{h}}33^{\text{m}}73 \pm 0.0015$	$30^{\circ}14.594 \pm 0.020$	$01^{\text{h}}90^{\text{m}}78 \pm 0.0021$	$32^{\circ}33.972 \pm 0.025$

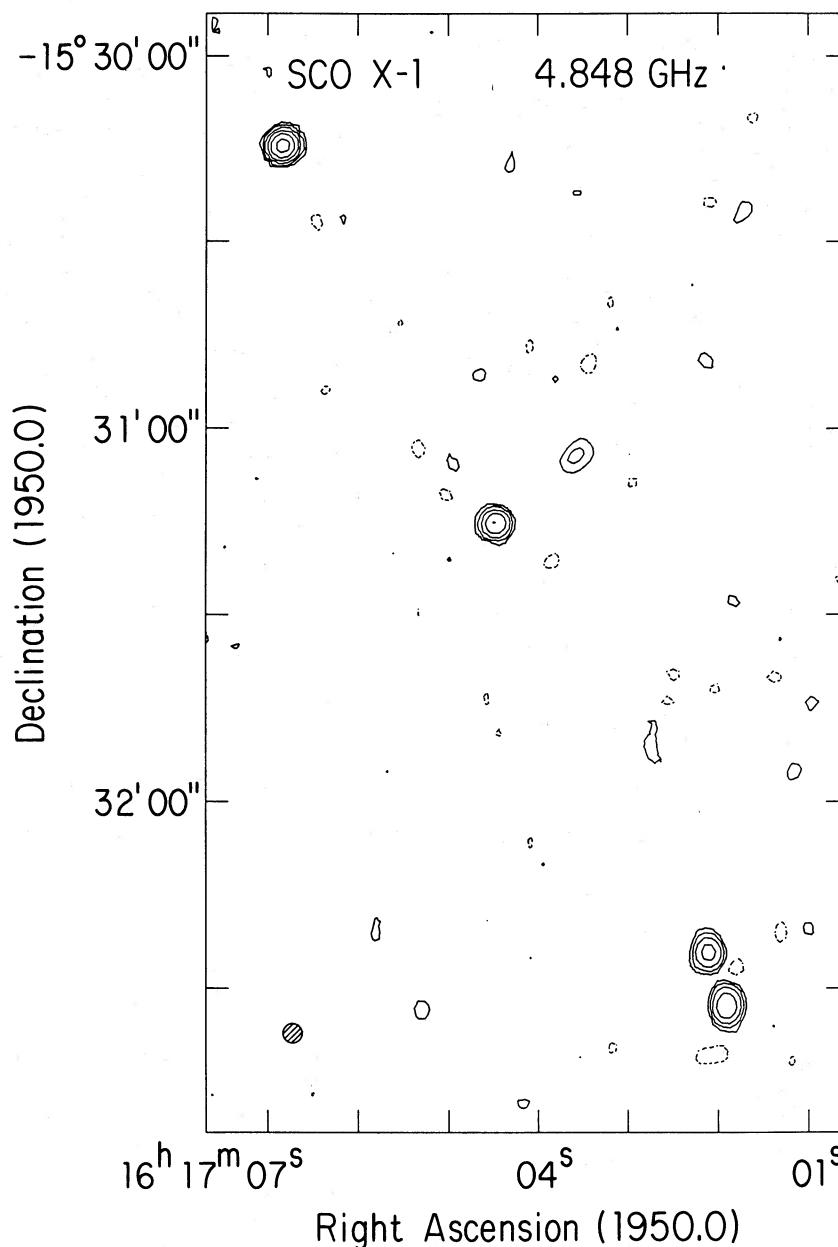


FIG. 1.—Radio image of Sco X-1. Contour diagram of the radio emission from Sco X-1 at 4.848 GHz with 3" resolution from the 1985 observations. Contour levels are at $-0.2, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4$ mJy per beam. FWHM beam size is shown by the cross-hatched circle in the upper right. Faint source $\sim 1'$ NW of the core is an unrelated background object.

obtained by the relation

$$E = \sqrt{[T^2 + (HN/P)^2]},$$

where T is $0''.02$, the radio astrometric uncertainty, H is the half-width half-maximum resolution ($0''.2$ E/W; $0''.25$ N/S), N is the rms noise in the image (see Table 1), and P is the peak flux density of the component (see Table 3). The values in Table 2 for the 1980, 1981, and 1982 observations are insignificantly different from those quoted in Paper II. The minimum accepted distance for Sco X-1 is 200 pc (500 pc is used in the later analysis), so that parallax corrections are less than the measurement errors and have not been made.

The position coordinates for each component were fitted to a linear relationship with time in a least-squares sense, and these results are displayed in Figure 3. In the fit each data point was weighted inversely proportionally with the error. Because of a possible discrepant point for the 1981 declination of the SW hot spot, solutions with and without this epoch have been determined.

The core and NE lobe show significant proper motion toward the south. When the 1981 observations are omitted, the SW hot spot also shows motion to the south. There is no significant proper motion in the east-west directions for any of the three components. The formal solutions for motion of the

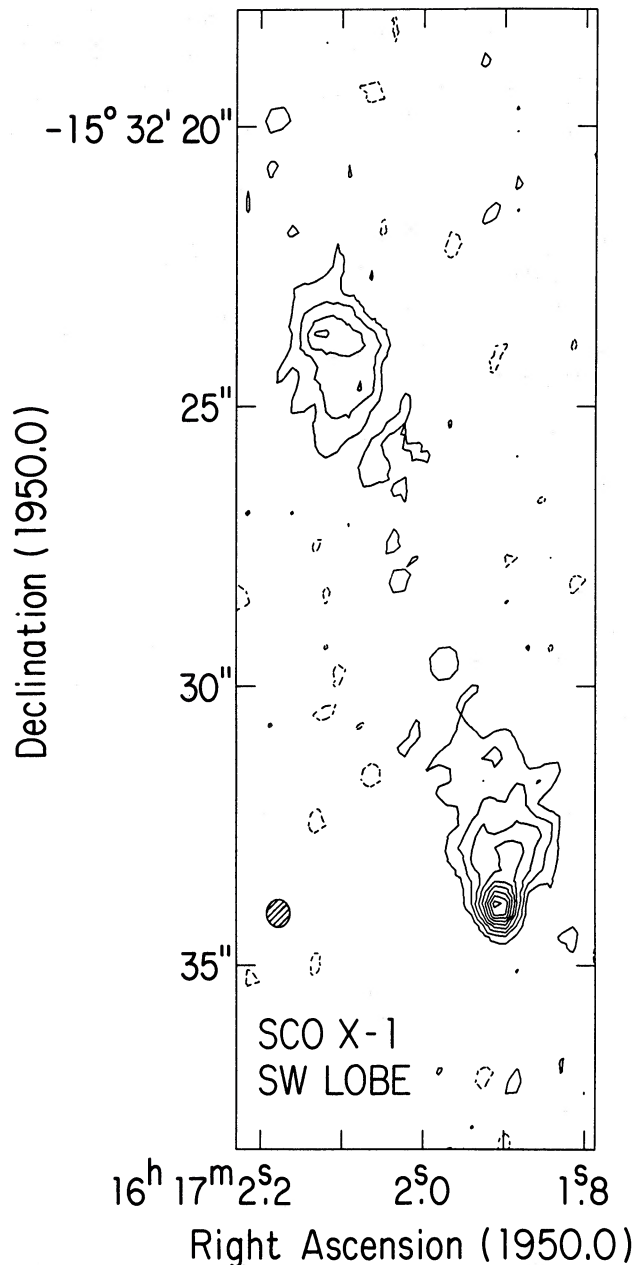


FIG. 2.—Radio image of the SW lobe of Sco X-1. Contour diagram of the radio emission from the SW lobe of Sco X-1 at 4.848 GHz with $0.5\text{ N/S} \times 0.4\text{ E/W}$ resolution from the 1985 observations. Contour levels are at 0.06 mJy increments with levels $-1, 1, 2, 3, \dots, 9$. FWHM beam size is shown by the cross-hatched ellipse in the upper right.

three radio components and the optical core (Sofia, Eichhorn, and Gatewood 1969) in the plane of the sky are

Optical core	$0.021 \pm 0.003\text{ yr}^{-1}$ in P.A. = $198^\circ \pm 7^\circ$;
Radio core	$0.035 \pm 0.005\text{ yr}^{-1}$ in P.A. = $189^\circ \pm 15^\circ$;
NE lobe	$0.022 \pm 0.004\text{ yr}^{-1}$ in P.A. = $170^\circ \pm 27^\circ$;
SW hot spot	$0.012 \pm 0.021\text{ yr}^{-1}$ in P.A. = $102^\circ \pm 85^\circ$, all epochs;

$$0.043 \pm 0.014\text{ yr}^{-1} \text{ in P.A.} = 176^\circ \pm 23^\circ, \\ \text{excluding 1981}$$

The correlation of the postfit residuals among the components is caused by the error in tying the position of Sco X-1 to the calibrators at each epoch.

The derived proper motion of the radio core is in good agreement with optical measurements of Sco X-1 between 1904 and 1968 (Sofia, Eichhorn, and Gatewood 1969). It is extremely unlikely that the general radio proper motion is produced by the northward motion of both calibrators since their relative position was unchanged by 0.02 over the 5 yr period. Other systematic errors which could produce a linear shift with time at the level of 0.02 yr^{-1} between 1981 and 1985 are extremely unlikely.

A comparison of the optical and radio positions at epoch 1983.0, after accounting for proper motion, is

Optical position	$16^{\text{h}}17^{\text{m}}04^{\text{s}}.474 \pm 0.007,$ $-15^\circ31'15''.44 \pm 0.10;$
Radio position	$16^{\text{h}}17^{\text{m}}04^{\text{s}}.465 \pm 0.005,$ $-15^\circ31'15''.21 \pm 0.08;$
Difference	$0.009 \pm 0.009,$ $-0.23 \pm 0.13.$

The major part of the optical position error is produced by the extrapolation of positions from the mean epoch of 1936. The major part of the radio position error comes from the estimated offset between the radio and optical grid (0.08). This offset can be greater than 0.2 in the southern hemisphere (see, e.g., Geldzahler and Fomalont 1984). Thus, the offset between the radio and optical positions of the core of Sco X-1 is probably not significant.

The relative separations between the NE lobe or the SW hot spot and the radio core are not affected by astrometric uncertainties in the grid, but are limited by the signal-to-noise ratio for each component. Other possible systematic differences between observations at the different epochs are minimized because of the nearly identical aperture coverage, the simplicity of the source morphology, and the use of identical software (the 1981 and 1982 results as reported in Paper II have been rederived with the improved AIPS software). These relative separations are shown in Figure 4. The errors are estimated from the quadrature sum of $H * N/P$ for each component, as discussed at the beginning of this section. The results of determining the best-fit linear slope through these data are

NE lobe-core:	$0.015 \pm 0.002\text{ yr}^{-1}$ in P.A. = $34^\circ \pm 7^\circ$;
SW hot spot-core:	$0.023 \pm 0.019\text{ yr}^{-1}$ in P.A. = $29^\circ \pm 75^\circ$, all epochs;
SW hot spot-core:	$0.004 \pm 0.012\text{ yr}^{-1}$ in P.A. = $106^\circ \pm 140^\circ$, excluding 1981.

These motions are not equal to the difference of the individual component proper motions because of the significantly reduced errors of the relative versus the absolute motions.

The motion of the NE lobe with respect to the core is significant at the five rms level. The direction of motion of $34^\circ \pm 7^\circ$ is very close to the position angle 29.4 of the line from the core to the NE lobe. The SW hot spot is not moving with respect to

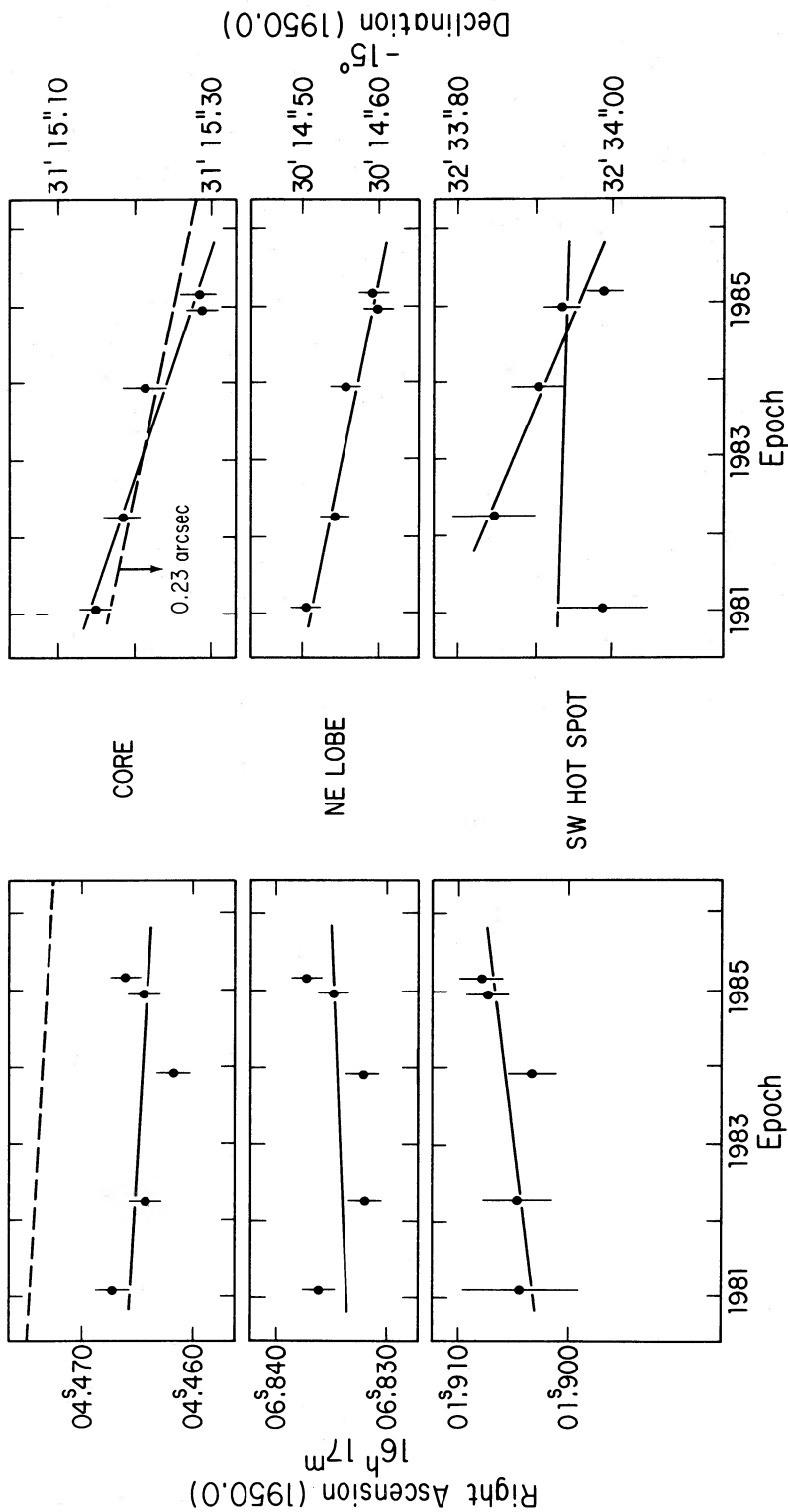


FIG. 3.—Absolute proper motion of the components. Measured right ascension and declination of the radio core, NE lobe, and SW hot spot for the five A-configuration observations. Solid line in each plot indicates the best fit to the proper motion. Two fits are given for the declination proper motion of the SW hot spot: one with all five epochs, and one excluding the 1981 observations. Dashed line in the core position plots shows the location of the star. The declination of the star has been offset by 0".23 to the north to more conveniently fit on the plot.

TABLE 3
FLUX DENSITY OF COMPONENTS IN SCO X-1

Epoch (yr)	Unresolved Core (mJy)	Unresolved NE Lobe (mJy)	Peak SW Hot Spot (mJy)	Integrated SW Lobe (mJy)
1980.108.....	16.3 ± 0.5	9.2 ± 0.4	...	7.9 ± 1.5
1981.098.....	10.21 ± 0.15	8.74 ± 0.28	0.45 ± 0.07	4.56 ± 0.21
1982.212.....	10.90 ± 0.24	10.06 ± 0.20	0.55 ± 0.07	6.61 ± 0.38
1983.910.....	1.05 ± 0.09	9.38 ± 0.12	0.40 ± 0.04	6.40 ± 0.15
1984.712.....	2.05 ± 0.18	10.15 ± 0.16	...	7.56 ± 0.21
1984.964.....	21.32 ± 0.44	10.47 ± 0.22	0.53 ± 0.04	4.72 ± 0.20
1985.183.....	3.26 ± 0.18	9.74 ± 0.15	0.47 ± 0.04	6.80 ± 0.44

the core with a limit of less than $0''.030 \text{ yr}^{-1}$ if we include all epochs, or a limit of less than 0.015 during the period 1982–1985. Thus, the velocity of the SW hot spot is not larger than about twice that for the NE lobe.

b) The Flux Densities of the Components

The flux densities of various components of Sco X-1 are listed in Table 3. The reanalysis of the 1981 and 1982 epoch data has yielded more accurate results than those published in Paper II. Because of the different angular sizes of the various components and the importance of determining realistic error estimates, some discussion of the methods are important.

The flux densities of the core and the NE lobe were obtained at each epoch by two methods. First, the integrated flux density and error estimate were determined from the Gaussian-fitting technique which was used to measure the position of the components. Second, the intensity was inte-

grated in a box of size $1''.4$, centered on each component. In order to determine a general image bias and error estimate for this second method, eight "control" boxes of identical size surrounding the central box were also integrated. The integrated flux density of the central box was corrected by the average flux density of the control boxes, and the error estimate of the integrated flux density of the central box was set equal to the average rms of the eight control boxes. The two methods gave consistent results, and the final value was equal to the average of the two methods. The quoted rms error was equal to the largest of the following: the error from the Gaussian fit; the error from the box integration; the difference between the two methods. This value is probably a slight overestimation of the true rms error.

The hot spot blends into the extended emission of the SW lobe; thus, its integrated emission is difficult to determine. By using the high-pass filtered image, we were able to determine a reliable peak flux density and error estimate for the hot spot with the Gaussian-fitting technique used to derive its position.

The integrated emission from the extended SW lobe was derived from the low-resolution $3''$ A-configuration images. For this extended component we used a rectangular box of $21''$ N/S by $13''$ E/W, centered on the component, and eight control boxes surrounding this central box. Gaussian fitting of the lobe with two or three components as a method for determining the integrated flux density was found to be unreliable. The flux densities of the core, NE lobe, and the entire SW lobe measured in the D-configuration with $12''$ resolution at epoch 1984.7 are also shown in the Table 3. From these images, the flux densities of all three components, which were nearly unresolved, were determined using the Gaussian-fitting method.

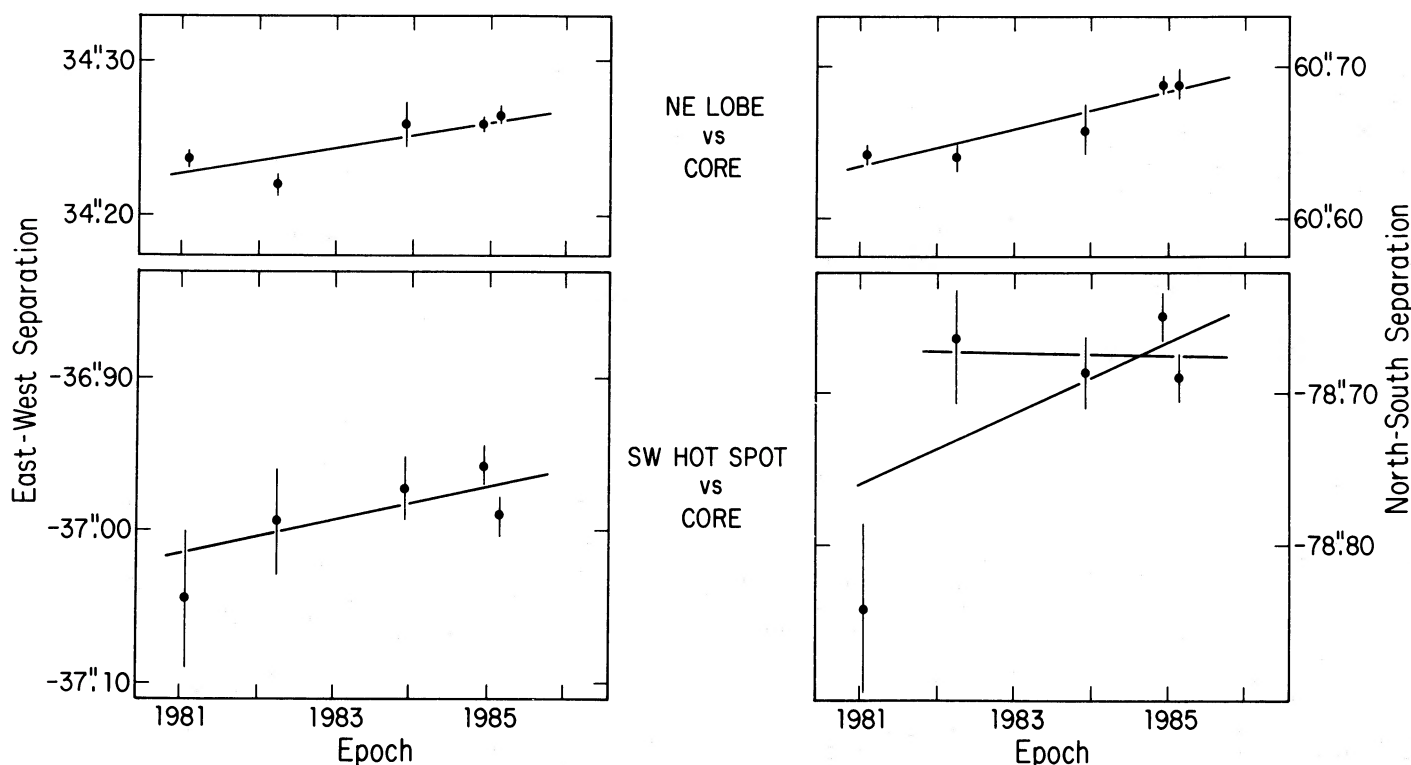


FIG. 4.—Relative motion of the NE lobe and the SW hot spot. Measured east/west and north/south displacements of the NE lobe and the SW hot spot from the radio core. Solid line in each plot indicates the best fit to the proper motion. Two fits are given for the declination proper motion of the SW hot spot: one with all five epochs, and one excluding the 1981 observation.

The difficulties in determining the integrated flux density of the extended components from synthesis data should not be underestimated (e.g., Fomalont in NRAO Synthesis Workshop, 1986). The D-configuration 1984.7 epoch observations in which the SW lobe was nearly unresolved should not be affected by these uncertainties. That this flux density determination is one of the largest is a bit disconcerting (could extended emission have been lost when integrating the flux density in the A-configuration images?), but the value is lower than the 1980.1 epoch measurement, and it is not out of line with the differences among the flux density measurements in general. We believe the extended emission in the SW lobe is variable, but additional D-configuration observations are needed to substantiate the variations.

IV. INTERPRETATION

The experimental results can be summarized as follows:

1. All components of Sco X-1 have an absolute proper motion which is nonzero and consistent with the proper motion of the star. Thus, there is no doubt of the physical association of the components with the X-ray emitting star.
2. There may be a slight difference between proper motions and positions of the radio core and the star. However, the differences are nearly within the expected errors.
3. The NE lobe is moving radially away from the core at a rate of $0''.015 \pm 0''.002 \text{ yr}^{-1}$.
4. The relative motion of the SW hot spot at the outer edge of the SW lobe has larger errors because of its weakness. Its motion is less than $0''.030 \text{ yr}^{-1}$ with respect to the core.
5. The assumption of linear motion of all three components is consistent with the postfit residuals. Any evidence of nonlinear motion (e.g., in the SW hot spot in declination in 1981) is too sparse at the present time.
6. The flux density of the core can vary by an order of magnitude in a period of 1 hr.
7. The NE lobe varies up to 20% in flux density over a period of 1 yr or less.
8. The SW hot spot may show variations of $\sim 20\%$, although these variations are less than ~ 3 times the error.
9. There may be a correlation between the flux density variation in the NE lobe and that of the SW hot spot (see Table 3). However, this conclusion should be checked with further low-resolution observations.
10. The integrated flux density in the SW lobe varies by $\sim 30\%$ over time scales of less than 1 yr, and the variations are not localized to a small region in the lobe.

V. DISCUSSION

a) General Features

The goal of this paper is to show the observational evidence for position changes and flux density variations within Sco X-1. We should, however, touch on some of the problems in the interpretation of the evolution of the source in terms of the current theories. With the measurements of motion and intensity variations of the radio lobes, Sco X-1 is a unique object in which to measure aspects of the interaction of the beam with the interstellar medium directly and, perhaps, the role of a magnetic field. It is likely that an understanding of the interactions in Sco X-1 can aid in the understanding of the more luminous radio galaxies and quasars.

We have established that the radio morphology of Sco X-1 is similar to that of luminous extragalactic radio sources which

consists of four basic parts: (1) an unresolved component which is nearly coincident with the X-ray and optical object; (2) two oppositely directed, well-collimated beams or jets in which some of this energy is transported away from the core; (3) bright regions (hot spots), somewhat symmetrically disposed around the core, where the bulk of the energy flow is converted into relativistic particles and magnetic fields; and (4) regions of diffuse emission which contain the debris of relativistic energy from the beam-hot spot interaction. Sco X-1 shows all but the second feature, the radio jets. Since the beams associated with a significant minority of extragalactic sources are undetected as radio jets with the same core-jet sensitivity contrast as Sco X-1 (the limit of the jet brightness in Sco X-1 is $\sim 0.15 \text{ mJy}$ per beam, compared with the core intensity of $\sim 10 \text{ mJy}$ per beam), the lack of jets in Sco X-1 is not surprising. VLB observations (Paper I) have not detected 1 mas jetlike protrusion from the core.

Throughout the following discussion we shall assume a distance of 500 pc to Sco X-1. This value is uncertain by a factor of 2 (see Paper II for details). At 500 pc, the angular size of $1''$ corresponds to $7.5 \times 10^{10} \text{ km}$, and a proper motion of $1'' \text{ yr}^{-1}$ corresponds to a velocity of 2370 km s^{-1} .

It is believed that the Sco X-1 binary system is composed of a degenerate star, either a white dwarf or a neutron star of mass less than $2 M_{\odot}$; and a secondary, slightly evolved main-sequence star with a mass of $2 M_{\odot}$, which fills its Roche lobe (Cowley and Crampton 1975). The galactic coordinates of Sco X-1 are $l = -1^{\circ}2$ and $b = 24^{\circ}2$. At the distance of 500 pc the source is 225 pc above the galactic plane. The measured proper motion of $65 \pm 20 \text{ km s}^{-1}$ (an average of the radio and optical determination) when corrected to the local standard of rest of Sco X-1 is $\sim 40 \text{ km s}^{-1}$ (assuming little radial velocity) and is nearly parallel to the plane. Hence, the binary system does not have a high space velocity.

Table 4 contains measured and derived physical parameters for each of the four components of Sco X-1. The spectral information on the components were derived from a comparison of the 1.5 and 4.85 GHz maps, and the radio luminosity was integrated between 10^7 and 10^{11} Hz . We have used the standard isotropic synchrotron-theory minimum energy assumption to derive the internal magnetic fields and pressure in the components. We assumed the unresolved features were circular with a diameter equal to the angular size limit, the extended emission in the SW lobe consisted of two ellipsoids of major axes $4'' \times 6''$, and there was equal relativistic energy in the electrons and protons. The scaling of all parameters for a distance 500z pc is given in the last column.

b) The Dilemma of the Slow Velocity

As pointed out in Paper II, the extremely slow advance and the small linear size of the NE lobe and SW hot spots are problems for all models of radio source confinement and evolution. In the conventional beam model (Blandford and Rees 1974), for which the hot spots are interpreted as the contact regions between the flow in the beam and the ISM, it is difficult to reconcile the large energy flux needed to power the lobes with the small momentum flow imparted by the hot spots on the ISM. From equation (3) in Paper II the mass density, p , needed to stop the advance, V , of the beam of energy flow of velocity, βc , is

$$p = L/(v^2 \beta c A E),$$

TABLE 4
MEASURED AND DERIVED PROPERTIES OF COMPONENTS OF SCO X-1

Property	Units	Core	NE Lobe	SW Hot Spot	SW Lobe	Scale
Flux density	10^{-3} Jy	10 ν	9.5	0.5	6.5	
Angular size		<0.1	<0.1	<0.15	12	
Spectral index		-0.3 ν	-0.3	-0.3	-1.4	
Linear size	10^{14} cm	<7.5	<7.5	<11.2	900	z
Working surface area	10^{28} cm ²	<44	<44	<44	<99	z^2
Volume	10^{45} cm ³	<0.44	<0.44	<1.49	39460	z^3
Luminosity	10^{28} ergs s ⁻¹	17.3	16.5	0.87	28.6	z^2
Minimum energy	10^{45} ergs	<0.52	<0.50	<0.16	491	$z^{1.7/7}$
Magnetic field	10^{-3} G	>11	>11	>3	1.1	$z^{-2/7}$
Pressure	10^{-6} dyne cm ⁻²	>5.9	>5.8	>0.5	0.06	$z^{-4/7}$
Radiative lifetime	10^3 yr	<0.27	<0.27	<1.89	174	$z^{3/7}$
Kinetic lifetime	1 yr		<6.7	<15?	300	

where the energy in the beam is L/E , with E being the efficiency of converting this energy into relativistic particles and fields and A the contact area between the beam and the ISM which is set equal to the size of the hot spot. Inserting the relevant parameters from Table 4 gives

$$n > 0.6/(E\beta) \quad \text{H atoms cm}^{-3} \text{ for the NE lobe,}$$

$$n > 0.03/(E\beta) \quad \text{H atoms cm}^{-3} \text{ for the SW hot spot,}$$

where n is the external density needed to stop the beam.

This density could be overestimated for several reasons. First, the distance to Sco X-1 may be larger than 500 pc, and the necessary stopping density would decrease by z^2 . Second, the true space velocity of the hot spots with respect to the ISM could be any value between 0 and 100 km s⁻¹. The measured transverse relative motion of the NE lobe with respect to the core of 35.5 km s⁻¹ does not include any contribution from the general motion of the binary system through the ambient medium, which we estimated to be ~ 40 km s⁻¹.

On the other hand, three uncertainties could push the estimated stopping density to much larger values. The NE lobe and SW hot spots are still unresolved and could be much smaller; much of the bulk energy in the beam may not be converted into radio energy; and the beam velocity could be substantially less than c . Furthermore, Sco X-1 could be as close as 200 pc, so the space velocity of the lobes could be less than 35.5 km s⁻¹.

The density of the ISM in the region of Sco X-1 is completely unknown. The density of the typical cool ISM is ~ 1.0 cm⁻³ (e.g., Turner 1979). The intense X-rays from the binary, however, could heat the ISM near the lobes to a temperature in excess of 10,000 K (Kallman and McCrea 1982), in which case the gas density could be less than 0.1 cm⁻³. Finally, Sco X-1 may be embedded in a dark nebula which is seen nearly in projection with the radio source (Sancisi and van Woerden 1970).

There are several alternative models which have been applied to Sco X-1. The radio lobes and hot spots may not be the location where a substantial part of the energy and momentum flux in the beam is converted. A model proposed by Achterberg, Blandford, and Goldreich (1983) suggests that a strong toroidal magnetic field around the beam may focus the flow into a small volume where strong shocks produce the radio emission in the hot spots. The flow, then, continues beyond the hot spot, every widening and decreasing rapidly in radio power. The predicted lobe morphology would consist of a bright hot spot and a lower brightness radio tail extending

outward from the core. The opposite morphology is seen the SW lobe. This model does not require an outward motion of the hot spots.

Although the pressure in the hot spots is 10^6 times larger than that in the normal interstellar medium, Kundt and Gopal-Krishna (1984) have suggested that the radio source is embedded in a dense H I molecular region formed by the interaction of the surrounding medium and the supernova remnant of Sco X-1 which was formed $\sim 3 \times 10^3$ yr ago. Only with a density of 10^5 cm⁻³ and a temperature of 10^3 K could the external pressure approach that needed for confinement of the NE hot spot. There are several objections to this model: (1) the characteristics of the binary system are not typical of a supernova, i.e., low space velocity (this paper) and a low orbital eccentricity (Cowley and Crampton 1975); (2) at the density and temperature required for sufficient confinement, significant amounts of optical and radio thermal brehmstrahlung should have been detected; (3) the estimate of the internal pressure from Paper I used by Kundt and Gopal-Krishna has been revised upward because of the additional observations; (4) it seems likely that Sco X-1 did not originate in a supernova explosion. Recent observations have shown Sco X-1 to be a quasi-periodic oscillator (van der Klis 1985; Middleton and Priedhorsky 1985), which in turn has been interpreted (see Lamb *et al.* 1985) as a weakly magnetic neutron star originating in the collapse of a white dwarf accreting matter in a binary star system.

c) Hot Spot Confinement

A major problem with Sco X-1 is the extremely small size of the NE lobe, less than 7.5×10^{14} cm. It takes less than 7 yr for the hot spot to transverse a distance which is equal to the upper limit size of the component. Since the lifetime of the radiating electrons are hundreds of years (based on equipartition arguments), the NE lobe should have an angular size which is $\sim 5''$ in size. A magnetic field strength of ~ 0.1 G, a factor 50 higher than the equipartition value, would decrease the synchrotron lifetimes to an acceptable level. However, a field strength of this magnitude would raise the internal pressure of the NE lobe to a level 10^9 times the interstellar value. The trade-off demonstrates the difficulty of finding a workable model for the source.

On the other hand, the kinetic lifetime of the SW lobe (the time needed for the hot spot to traverse the distance of the lobe) is comparable to the electron radiative lifetime, and the steepness of spectral index of the radio emission back from the

SW hot spot does suggest synchrotron spectral aging. The internal lobe pressure of 6×10^{-8} dyne cm^{-2} could be confined by an external medium or by magnetic confinement.

d) Flux Density Variations

The flux density variations of the NE lobe and the SW hot spot may reflect on the detailed interaction of the beam and the ISM and on the net energy flow in the beam. The component sizes are less than 1 lt-day, and variations have not been seen at these short time scales, whereas they have for the core. The possible variations in the extended region of the SW lobe, whose size is ~ 35 lt-days, may be consistent with fast flow of the electrons and field generated at the hot spots back into the lobe. Variations in the generation of relativistic plasma would then quickly disperse through the lobe, although the details of how 20% variations over 6 month periods could occur are unclear.

We should not rule out coherent types of radiation processes in which the radiation field is not isotropic and the variations are caused by changes in viewing angle of the coherent electron orbits and the line of sight. Further analysis of the multi-frequency polarization data may shed some light of this possibility.

VI. CONCLUSIONS

We have detected motion and variability in the radio lobes of the binary X-ray source Sco X-1. The twin-exhaust beam model of energy transport from the core to the lobes is the

most acceptable model for the evolution of the source. However, the needed density to restrain the outward motion of the lobes to 35.5 km s^{-1} may be much larger than expected for the ISM at 225 pc above the plane.

The small size of the NE lobe is best explained by a magnetic field at least as large as 0.1 G, ~ 50 times that expected from the usual synchrotron equipartition calculations, but confinement by a high-density surrounding cloud cannot be excluded. The measured variations of the flux densities of the components are not inconsistent with the size of the components; however, the plasma must migrate from the SW hot spot at velocities which are mildly relativistic in order to explain the variations in the extended SW lobe. Because of the difficulty in understanding the evolution of this source, coherent synchrotron or other radiative processes should be investigated.

Further monitoring of the flux density and motion of Sco X-1 are important to understand the interaction of the energy flow from the core and its interaction with the ISM. Over the past 5 yr the motion has been linear, which suggests that the beams are now traversing a relatively uniform medium with a size scale greater than 10^{15} cm. A detailed analysis of the spectral and polarization properties of the source may aid in interpreting the source.

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EDWARD B. FOMALONT: National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA 22901

BARRY J. GELDZAHLE: Naval Research Laboratory, Code 4120, Washington, DC 20375