

A MEASUREMENT OF THE LOCATION OF THE X-RAY-SOURCE SCO X-1

We have measured the location of Sco X-1, the strong X-ray source in Scorpio, with a precision of about 1 arc min. Sco X-1 was first observed in X-rays by Giacconi, Gursky, Paolini, and Rossi (1962) during a rocket experiment in 1962 at which time its location could only be roughly estimated. A subsequent observation by Bowyer, Byram, Chubb, and Friedman (1964*a*) yielded a location with a precision of about 1° , and more recent measurements of its position have been reported by Clark, Garmire, Oda, Wada, Giacconi, Gursky, and Waters (1965) and by Fisher, Johnson, Jordan, Meyerott, and Acton (1966). The location derived from the present measurement is shown in Figure 1 and listed in Table 2 (see below).

The data which yield the present result were obtained with an instrumented payload flown on a stabilized Aerobee rocket from White Sands Missile Range, New Mexico, on March 8, 1966. The recent report by Gursky, Giacconi, Gorenstein, Waters, Oda, Bradt, Garmire, and Sreekantan (1966) that the angular size of Sco X-1 is less than 20 arc sec was based on the same data.

The Aerobee rocket was equipped with an attitude-control system that allowed pointing to a prescribed direction on the celestial sphere with a precision of a few degrees. While pointing, the rocket axes were restricted in their motion to a 1° limit cycle, and the rate of motion within the limit cycle was typically several arc minutes per second of time.

The instrumentation included a group of proportional counters which detected the X-rays transmitted through two modulation collimators. It also included a camera that continuously recorded the celestial orientation of the collimators. The specifications of the instruments are listed in Table 1. Individual pulses from the X-ray counters were stretched to 0.5 msec with their amplitude preserved and telemetered to a ground receiver. The time at which the photographs were taken was recorded by telemetering the pulse that advanced the camera. The aspect photographs were recovered from the payload after the rocket flight.

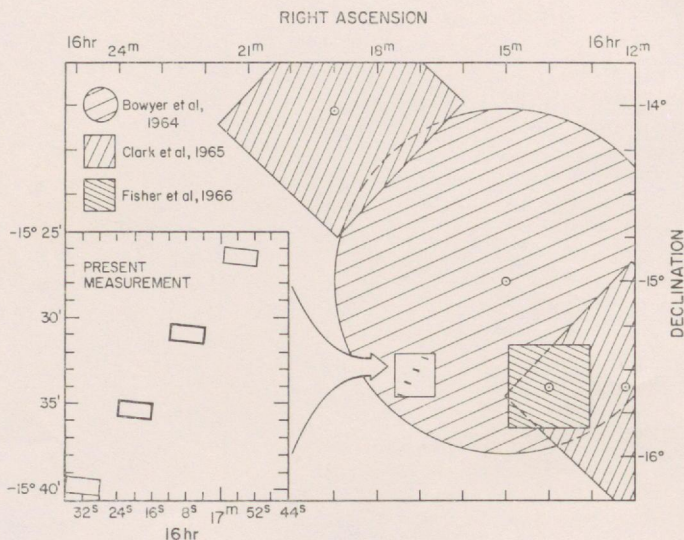


FIG. 1.—The location of Sco X-1. The results of the present experiment are shown with results from previous experiments.

TABLE 1
INSTRUMENTATION SPECIFICATIONS

Modulation collimators:

Band width:	
Long collimator.....	72"
Short collimator.....	76"
Separation between bands:	
Long collimator.....	5'1".91
Short collimator.....	5'16".62

Aspect camera:

Body.....	16-mm Millikan (Model DBM-3C)
Lens.....	f 1:1.4, 50-mm Cooke
Film.....	Tri-X on Estar base

X-ray detectors:

Operating mode.....	Proportional region
Gas filling.....	Xenon at one atmosphere
Entrance window.....	9.0 mg/cm ² beryllium
Sensitive area.....	120 cm ² behind each collimator (5 individual detectors)
X-ray region of sensitivity.....	1.5 keV < E < 30 keV (efficiency > 20 per cent)

The angular response of the modulation collimators for X-rays consisted of a series of parallel bands separated by about four times their width (see Fig. 1 of Gursky *et al.* 1966). High angular resolution was achieved only in the direction normal to the bands. The transmission bands covered a broad field of view which allowed the observation of a given source without the necessity for particularly good pointing accuracy. The use of two modulation collimators with slightly different angular response made it possible to determine from which particular band in a given collimator the X-rays were arriving. The two modulation collimators were aligned with respect to each other to make their transmission bands nearly parallel.

The orientation of the collimator transmission bands in the sky was determined from photographs taken by the aspect camera at a 1 per sec rate. The camera lens simultaneously viewed the star field through an opening between the collimators and a diffuse-light source mounted in front of each collimator. The diffuse light was preferentially transmitted by the collimators in the same directions as were X-rays. The photographic image formed by the transmitted light was a series of bands of complex appearance due to diffraction effects. Through laboratory calibrations we established a unique correspondence between the position of these bands and the X-ray transmission directions. Thus, since star images appeared on the same photograph with the bands, the X-ray transmission directions could be directly determined with respect to the celestial sphere. There was no necessity to align the collimators with respect to the aspect camera or to maintain a fixed alignment during the flight. An example of one of the aspect photographs appears in our earlier paper (Gursky *et al.* 1966).

During the flight, Sco X-1 was observed for about 55 sec. The X-ray data taken during that portion of the flight are shown in Figure 2. A series of peaks occur in the data, each one coinciding with a transit of the source across one of the transmission bands of the collimator. The variations in the time between peaks and in the shape of the peaks for a given collimator are caused by changes in the drift rate of the rocket axes.

Figure 3 shows a plot of the coordinates of the center of the aspect photographs and the orientation of the sensitive direction (the direction normal to the X-ray transmission bands) of the modulation collimators. No peaks were observed in the counter data during the times 303–317 sec, and it is clear from the aspect data that the rocket was virtually motionless during much of that time. At $t = 325$ sec, the rocket began a programmed roll of $4\frac{1}{2}$ /sec around the central axis of the collimator. At about the same time aerodynamic effects (the rocket was beginning to re-enter the atmosphere) became noticeable and tended to force the rocket nose downward at an increasing rate. By 340 sec the X-ray source had drifted out of the field of view of the collimators.

Each time a peak in the counting rate is observed we can compute a set of narrow parallel bands in the sky separated by about 5 arc min on which the source must lie. The number of possible locations can be substantially reduced by comparing the data from the two collimators which are constructed so that they differ by about 5 per cent in the angular separation of their transmission bands. Twenty bands from the "short" collimator are separated by about the same total angle as twenty-one bands from the "long" collimator. Thus, the two collimators provide a vernier scale, which is repeated every $1^{\circ}40'$, the equivalent of those numbers of bands. Figure 4 shows the projection on the sky of the allowed transmission bands of the collimators. As the source traverses the field of view, peaks in the counting rate will be observed, first in one and then the other collimator. The relative times of occurrence of these peaks determine, after conversion to relative angles, which transmission band within the vernier scale corresponds to a given peak. This defines a series of bands separated by about $1^{\circ}40'$ on which the source must lie.

The experiment itself provided a coarse position measurement that allowed us to decide on which particular band the source lies. Five individual detectors were used behind each collimator to detect the transmitted X-rays. The upper edge of the colli-

meters casts a shadow on the detectors. The position of the shadow was found by comparing the counting rates of the individual detectors. This, in turn, determined the angle between the X-ray source and the central axis of the collimator with a precision of better than 1° .

Given the motion of the detector axis from the aspect data we are able to follow the transit of the X-ray source from band to band throughout the flight. Once the vernier technique has established which specific band is traversed at any given time, we know which specific band is traversed at any other time. During the time when no appreciable

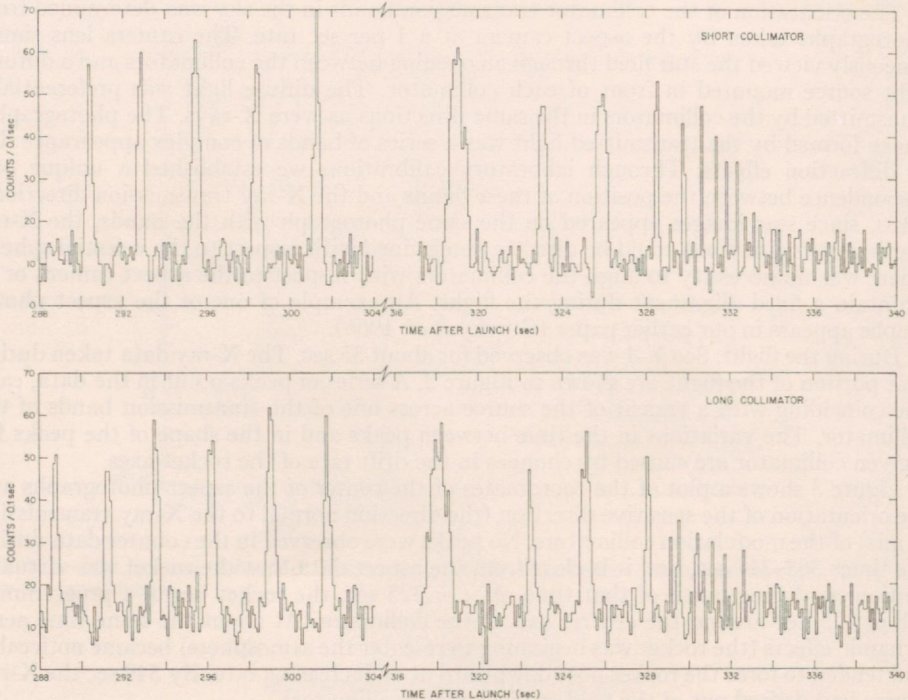


FIG. 2.—Histogram of actual counts in the energy range from 1 to 24 keV and accumulated per 0.1 sec during the time that Sco X-1 was within the field of view of the collimators.

rotation of the sensitive axis occurs, successive transits define the same line on the celestial sphere. As the sensitive direction rotates by a given angle the appearance of a maximum defines a new line tilted by that angle with respect to the previous determination. The source must be at the intersection of these two lines. The procedure is repeated for every appearance of the peak as the rotation takes place, thus resulting in a set of intersections. The average of these is taken to be the location of the source.

In practice, the experimental uncertainties in the measurement of location by the method outlined above result in the following: (1) a lack of uniqueness in the assignment of a source position; hence we list two most likely positions in Table 2; (2) an area of uncertainty around each individual position.

Our inability to assign a single source position arises from uncertainties in measuring the relative orientation of the two sets of collimator bands as recorded on the aspect photographs. One source of this uncertainty was our imprecise knowledge of the correspondence between the X-ray transmission directions and the visible light bands. The

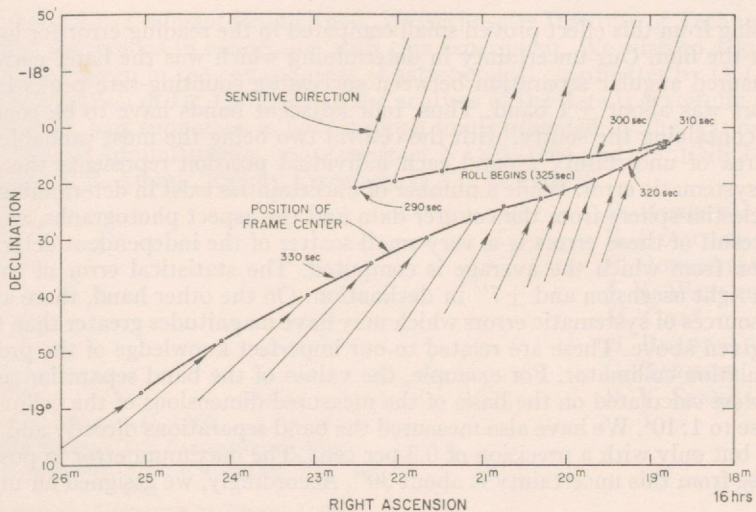


FIG. 3.—Motion of the frame center and orientation of the sensitive direction during the observation of Sco X-1. The frame center, which is defined as the geometric center of the aspect photographs, was approximately aligned with the central axes of the modulation collimators. Dots indicate 2-sec intervals from 290 to 310 sec, and 1-sec intervals from 310 to 333 sec.

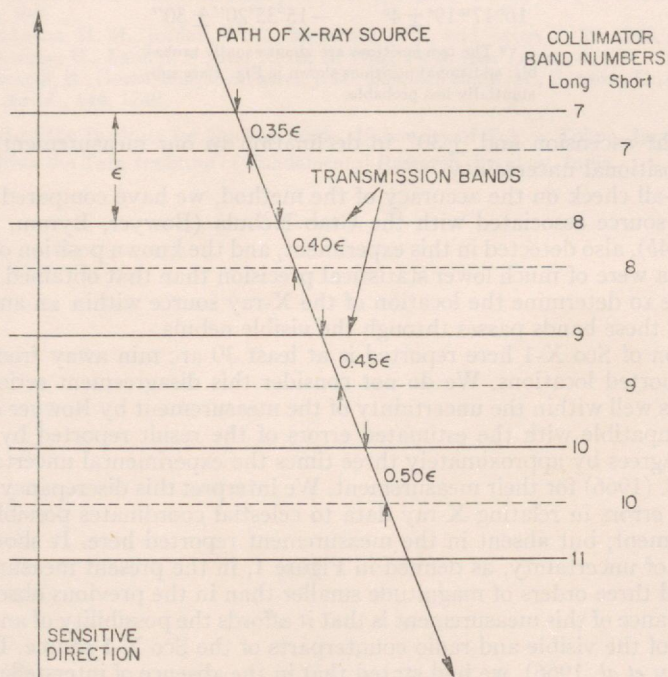


FIG. 4.—Schematic representation of several of the X-ray transmission bands from the two collimators as they appear on the aspect photographs. As successive pairs of bands are traversed, the angular separation of source transits, across correspondingly numbered bands, increases by about 0.05ϵ .

error arising from this effect proved small compared to the reading error for locating the bands on the film. Our uncertainty in determining which was the band corresponding to a measured angular separation between successive counting-rate peaks in the two collimators was about ± 1 band. Thus, four adjacent bands have to be considered as possibly containing the source, with the central two being the most probable bands.

The area of uncertainty around each individual position represents the estimated range of systematic error. While a number of uncertainties exist in determining positions on the celestial sphere from the counter data and the aspect photographs, we find that the net result of these errors is a very small scatter of the independent determinations of position from which the average is computed. The statistical error of the average is $\pm 2^s$ in right ascension and $\pm 7''$ in declination. On the other hand, there are several possible sources of systematic errors which may have magnitudes greater than the uncertainties given above. These are related to our imperfect knowledge of the properties of the modulation collimator. For example, the values of the band separation as listed in Table 1 were calculated on the basis of the measured dimensions of the collimators and are precise to $1:10^4$. We have also measured the band separations directly and find them to agree, but only with a precision of 0.3 per cent. The maximum error in position that could arise from this uncertainty is about $30''$. Accordingly, we assigned an uncertainty

TABLE 2
BEST POSITIONS OF SCO X-1 DETERMINED IN THIS EXPERIMENT*

$\alpha(1950.0)$	$\delta(1950.0)$
$16^h 17^m 7^s \pm 4^s$	$-15^\circ 30' 54'' \pm 30''$
$16^h 17^m 19^s \pm 4^s$	$-15^\circ 35' 20'' \pm 30''$

* The two positions are about equally probable; additional positions shown in Fig. 1 are substantially less probable.

of $\pm 4^s$ in right ascension and $\pm 30''$ in declination to our measurement as our best estimate of positional uncertainty.

As an over-all check on the accuracy of the method, we have compared the location of the X-ray source associated with the Crab Nebula (Bowyer, Byram, Chubb, and Friedman 1964*b*), also detected in this experiment, and the known position of the nebula. While the data were of much lower statistical precision than that obtained for Sco X-1, it was possible to determine the location of the X-ray source within an ambiguity of 4 bands. One of these bands passes through the visible nebula.

The location of Sco X-1 here reported is at least 30 arc min away from any of the previously reported locations. We do not consider this disagreement serious since the new location is well within the uncertainty of the measurement by Bowyer *et al.* (1964*a*) and not incompatible with the estimated errors of the result reported by Clark *et al.* (1965). It disagrees by approximately three times the experimental uncertainty quoted by Fisher *et al.* (1966) for their measurement. We interpret this discrepancy as being due to systematic errors in relating X-ray data to celestial coordinates possibly present in their measurement, but absent in the measurement reported here. It should be noted that the area of uncertainty, as defined in Figure 1, in the present measurement is between two and three orders of magnitude smaller than in the previous observations.

The significance of this measurement is that it affords the possibility of an unequivocal identification of the visible and radio counterparts of the Sco X-1 source. In a previous Letter (Gursky *et al.* 1966), we had stated that in the absence of interstellar absorption the visible image of this X-ray source should appear as a starlike object of 13th magnitude or brighter. On the basis of the earlier conclusions and of the present result, an optical identification has been made and is reported in the following companion Letter.

We are grateful to Professor Bruno Rossi, Massachusetts Institute of Technology, for many helpful discussions in connection with this experiment. We wish to acknowledge the contribution given in the computation of astronomical coordinates by G. Ouellette. Also, the contribution of Dr. G. Spada to the analysis of the data is gratefully acknowledged. This work was supported in part through funds provided by the National Aeronautics and Space Administration under contract NASW-1284 and grant NSG-386, and in part by the U.S. Atomic Energy Commission AT(30-1) 2098.

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ON THE OPTICAL IDENTIFICATION OF 200 X-1

An optical search has been made of the sky surrounding the new position of 200 X-1 described in the preceding Letter (Gursky, Giacconi, Gosselin, Warner, Oda, Hsieh, Giacconi, and Stecker 1966). Preliminary results of the measurement were made available to the Tokyo Observatory and to Bolman. The search, which we believe has been successful, was based on these results and on the working hypothesis that the image should (1) appear starlike, (2) be of at least 14th apparent visual magnitude and (3) have an ultraviolet excess relative to normal stars. The first two requirements are stated in the discussion of Gursky et al. (1966) on the measurement of an optical limit of 30" to the diameter of 200 X-1. The predicted lower limit on the visible magnitude was obtained by extrapolating the energy distribution from the observed range of 1-10 Å into the optical region in the assumption of a spectrum that is flat per unit frequency interval. Such a spectrum could result from either bremsstrahlung or synchrotron emission (Mariani 1965) and requires, in the optical region that $kT \approx 0.10$ mag, and $kT \approx 0.21$ mag (Giacconi and Saragolla 1967, Table A4 for $n = 0$).

A two-color image plate taken on Eastman 103A0 emission with the Tokyo Observatory's 74-inch reflector on June 17, 1966 covered a region from about $\delta = 195^{\circ} 50'$ to $195^{\circ} 54'$ and $\alpha = 1^{\circ} 30'$ to $1^{\circ} 34'$ between $18^{\circ} 12'$ and $18^{\circ} 13'$. An ultraviolet and a blue image of each star was obtained through a Broy U3 filter ($\lambda = 3600 \text{ Å}$) and a

ON THE OPTICAL IDENTIFICATION OF SCO X-1

An optical search has been made of the sky surrounding the new position of Sco X-1 described in the preceding Letter (Gursky, Giacconi, Gorenstein, Waters, Oda, Bradt, Garmire, and Sreekantan 1966a). Preliminary results of the measurement were made available to the Tokyo Observatory and to Palomar. The search, which we believe has been successful, was based on these results and on the working hypothesis that the image should (1) appear starlike, (2) be of at least 13th apparent visual magnitude, and (3) have an ultraviolet excess relative to normal stars. The first two requirements are stated in the discussion of Gursky *et al.* (1966b) on the measurement of an upper limit of 20" to the diameter of Sco X-1. The predicted lower limit on the visible magnitude was obtained by extrapolating the energy distribution from the observed range of 1-10 Å into the optical region in the assumption of a spectrum that is flat per unit frequency interval. Such a spectrum could result from either bremsstrahlung or synchrotron emission (Manley 1966) and requires, in the optical region that $B - V \simeq 0.10$ mag., and $U - B \simeq -0.91$ mag. (Matthews and Sandage 1963, Table A4 for $n = 0$).

A two-color image plate taken on Eastman 103aO emulsion with the Tokyo Observatory's 74-inch reflector on June 17/18, 1966 covered a region from about δ (1950) between -15° and -16° and α (1950) between $16^h 15^m$ and 16^h and 18^m . An ultraviolet and a blue image of each star was obtained through a Hoya U2 filter ($\bar{\lambda} \simeq 3600$ Å) and a

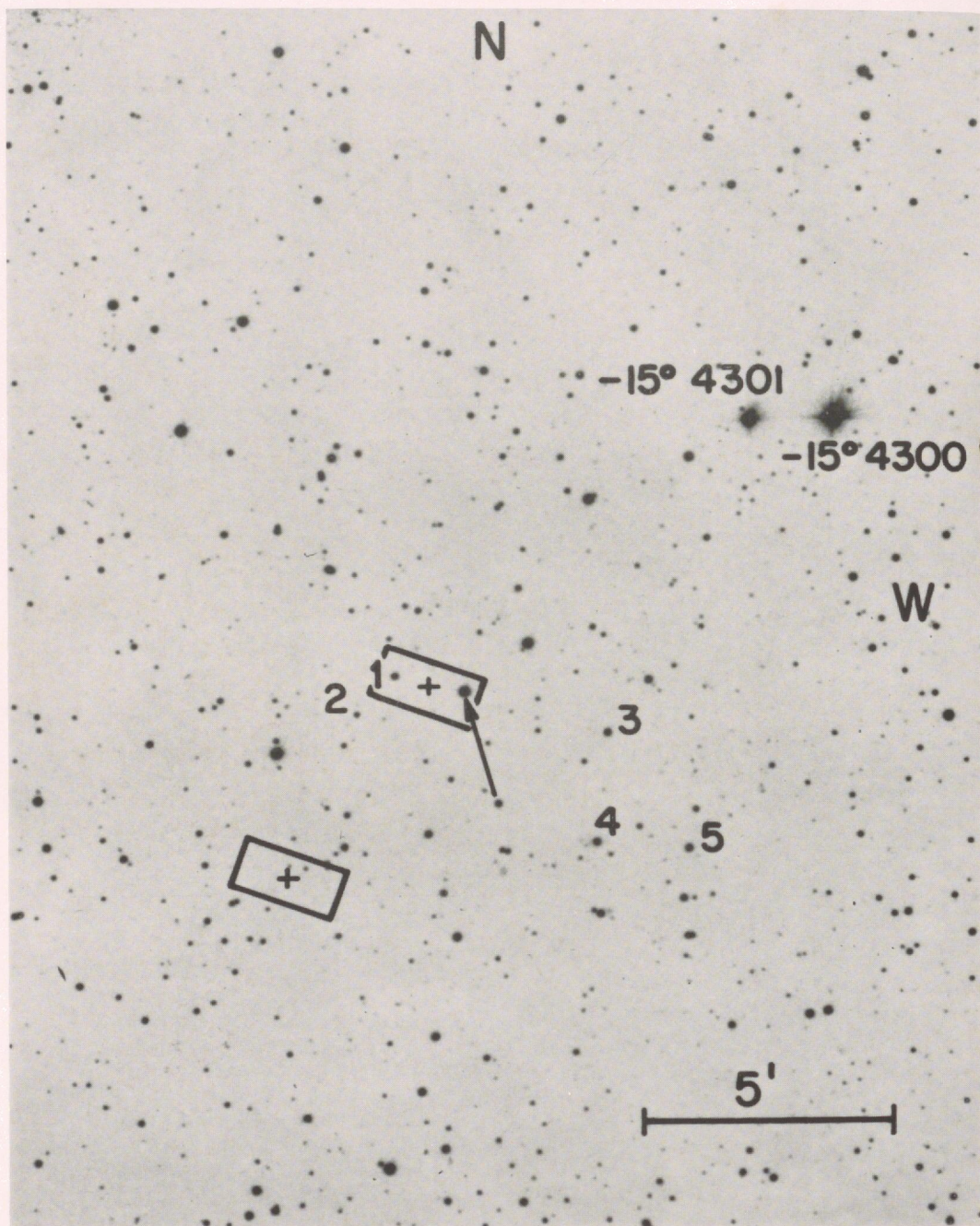


FIG. 1.—Photograph of the region containing the new X-ray position of Sco X-1, reproduced from the Palomar Sky Survey prints. The two equally probable X-ray positions are marked by crosses surrounded by a rectangle of 1 by 2 arc min. The object described in the text is marked with an arrow. The identifications of other stars for which photoelectric photometry exists are also marked.

Hoya L-39 filter ($\bar{\lambda} \simeq 4400 \text{ \AA}$). Immediate inspection of the plate revealed the existence of an intense ultraviolet object of $V \simeq 13$ mag. near the center of the search area and within 1 arc min of one of the two X-ray source positions quoted in the preceding Letter. Photoelectric photometry was secured of the object on the same night with the 36-inch reflector of the Tokyo Observatory, and the observation was repeated on June 22/23, 1966. Although frequently interrupted by clouds, which are prevalent in Japan during this rainy season, the observation gave $V = 12.6 \pm 0.2$ (m.e.), $B - V = +0.3 \pm 0.05$ (m.e.), and $U - B = -0.8 \pm 0.1$ (m.e.)—colors which are definitely peculiar and in the range predicted by the working hypothesis.

A spectrogram was obtained on June 18/19 at the Cassegrain focus of the 74-inch telescope with a two-prism quartz spectrograph which gives a dispersion of 90 \AA/mm at 4000 \AA and 150 \AA/mm at $H\beta$. The spectrum, which was underexposed because of unfavorable sky conditions, showed a continuum with no absorption features and with faint emission at $H\gamma$ and $\lambda 4686$.

These results were communicated by cable to Giacconi, who relayed them by telephone to Palomar on June 23, P.S.T. Photoelectric observations made with the 200-inch reflector on the same night confirmed the colors measured in Japan, giving $B - V = +0.23$, $U - B = -0.88$, each with statistical measuring errors of less than ± 0.01 mag. The data further showed that the object varies. Repeated observations, made with a pulse counter and separated from each other by less than 1 min in time gave differences in the total count which were 35 times greater than the statistical \sqrt{N} uncertainty. The object was monitored for 42 min on June 23 during which time its V magnitude changed irregularly from 12.44 to 12.38. The time scale of the fast flicker is of the order of 2 per cent (0.02 mag.) in several minutes. In one interval the U magnitude changed by 0.09 mag. in 8 min.

The flickering activity, together with the very peculiar colors, showed that the object has characteristics of old novae near their minimum phase. Walker's (1954, 1957) systematic survey of the photometric properties of old novae, nova-like variables, and U Gem stars showed that abnormal intensities in the ultraviolet and rapid changes in the continuum level are characteristic of the class. The object in question was tentatively identified as a member of this class on the basis of the data available by the end of June.

A second spectrogram of improved quality was obtained at the Tokyo Observatory on June 25/26, 1966. The emission features of $H\beta$, He II ($\lambda 4686$), $H\gamma$, $H\delta$, and possibly $H\epsilon$ were now clearly visible, again on a very blue continuum.

The optical position of the object was measured both at Tokyo and at Mount Wilson-Palomar with the result $\alpha(1950) = 16^{\text{h}}17^{\text{m}}4.3^{\text{s}}$, $\delta(1950) = -15^{\circ}31'13''$. This position is not definitive by astrometric standards because a refined reduction procedure using the astrographic and Yale Zone catalogues has not yet been used. Nevertheless, the position should be good to about ± 5 arc sec which is sufficient for the present purpose.

Figure 1 shows the field as reproduced from the Palomar Sky Survey prints. The two equally probable X-ray positions are shown as crosses surrounded by a rectangle of 2 by 1 arc min, corresponding to the quoted position uncertainty. The unusual blue object we have been describing is indicated by an arrow. There is no conspicuous object brighter than $V \simeq 16$ mag. in the alternate square. Furthermore, a survey of the Tokyo two-color plate shows that there is no other ultraviolet star within $\pm \frac{1}{2}^{\circ}$ of the new X-ray position.

Also identified in Figure 1 are several stars whose UBV values have been measured so as to obtain an estimate of the absorption and reddening in this direction of the sky. Table 1 shows the results and indicates that $E(B - V) \simeq 0.23$ out to an apparent distance modulus of $m - M \simeq 8.7$. These reddening values, obtained by using the usual two-color diagram, indicate a rather uniform absorption in V wavelengths of 0.7 mag. over the distance interval between $(m - M)_{\text{true}}$ of 5–8 mag. (100–400 pc). Thus interstellar absorption and reddening do not adversely affect the observation of Sco X-1 in visible light.

Simultaneous photoelectric and spectroscopic observations were begun at Palomar using the 200-inch and 20-inch reflectors. Photometry with the 200-inch on July 12 gave $\bar{V} = 12.95$ with a range of $\Delta V = 0.08$ mag. in the 12-min observation interval. The colors remained relatively stable at $B - V = +0.20$, $U - B = -0.76$. These values are appreciably different from $\bar{V} = 12.39$, $B - V = +0.23$, and $U - B = -0.88$ measured two and a half weeks earlier on June 24 U.T. Continued observations on 7 successive nights with the 20-inch telescope, primarily in the B wavelength band ($\lambda\lambda$ 3800–5400 Å), are shown in Figure 2. Spectra were obtained during the times indicated by the horizontal bars on July 13–July 18.

Figure 2 shows that the object is highly unstable in its continuum radiation, resembling the behavior of the probable old nova MacRae +43° 1 which Walker (1954) discovered to have rapid optical variations. The fluctuations also resemble, but to a

TABLE 1
PHOTOMETRY OF STARS IN THE FIELD OF SCO X-1

Object	V	$B - V$	$U - B$	$E(B - V)$	$(m - M)_{BPP}$	Remarks
-15°4300.....	8.5	0.25	+0.22	0.20	5.8	
-15°4301.....	9.88	0.33	+ .27	.23	6.7	
1.....	14.97	0.94	+ .41	.28	8.4	
2.....	16.25	1.05	+ .43	.46	9.2	
3.....	14.17	1.16	+ .87	.21	6.7	
4.....	14.47	0.84	+ .33	.18	8.4	
5.....	14.46	0.83	+ .26	0.27	8.6	
	12.43	0.23	- .86			June 24 U.T., 1966 selected data over a time interval of 43 min
	12.44	0.23	- .84			
	12.39	0.22	- .92			
	12.38	0.24	- .89			
	12.38	0.24	- .91			
	12.43	0.22	- .88			
SCO X-1.....						
	13.01	0.21	- .76			July 12 U.T., 1966 data over a time in- terval of 12 min
	12.97	0.20	- .73			
	12.94	0.20	- .74			
	12.95	0.19	- .76			
	12.94	0.21	- .76			
	12.93	0.21	-0.76			

lesser degree, the changes in the nova-like irregular variable AE Aquarii (Lenouvel 1957; Walker 1962). The intensity of our candidate star varied by 0.5 mag. in a 2.6-hour period on July 12 with the more rapid flicker variations which were observed on the same night at the 200-inch, presumably superposed on the decline shown in Figure 2. The variation in the general intensity level from night to night is evident, especially on the nights of July 16, 17, and 18, where the change is at least 0.9 mag.

The object has been located on old plates in the Harvard collection going back as far as 1896. Garmire and Sreekantan have inspected the Harvard material with the results shown in Figure 3 from 1935 to 1949. The variations in magnitude are real, but since no special observations were made for the photometric zero point or the scale of the comparison stars used for these estimates, the ordinate in Figure 3 is somewhat arbitrary and is not on the international m_{pg} system. Nevertheless, the data, including one point in 1896 at 12.4 mag., one in 1901 at 12.5 mag., two in 1913 at 12.5 mag. and one point in 1914 at 12.5, show that the object has been in its present state for at least 70 years with no evidence of a strong outburst in this period. However, the time coverage has not been tight enough to exclude a recurrent nova outburst with a decay time of less than a year sometime in the interval.

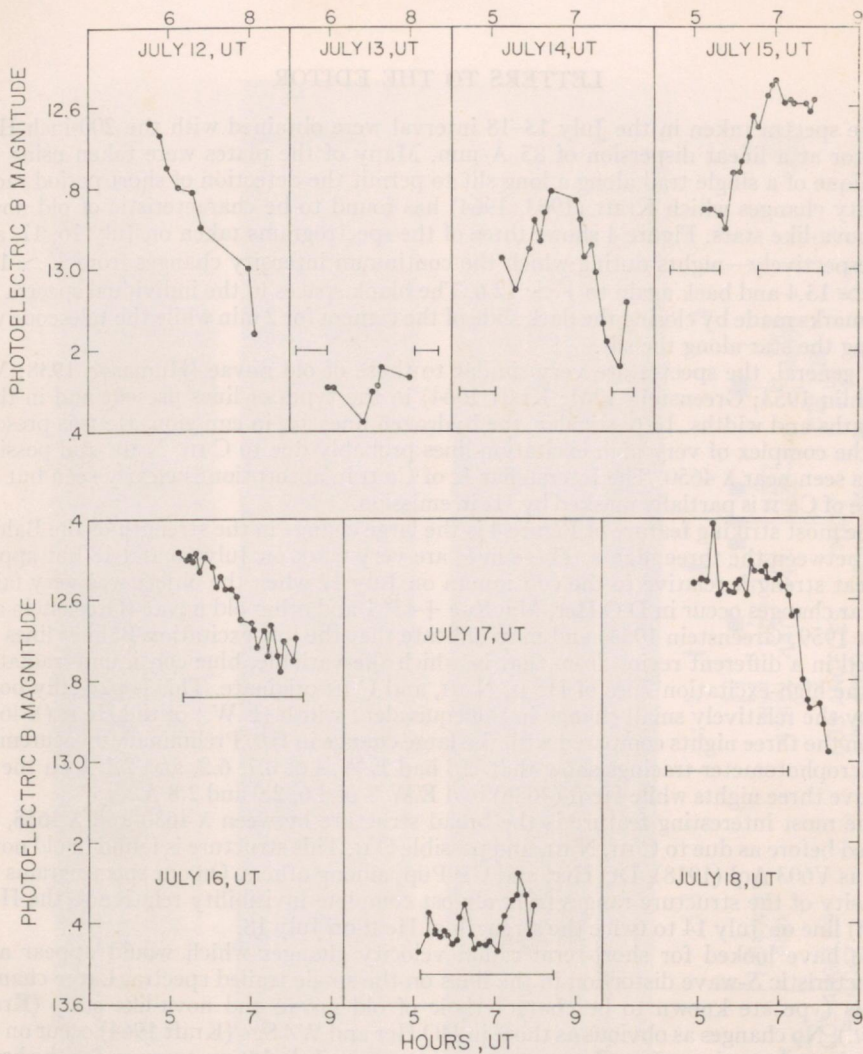


FIG. 2.—Photoelectric *B* magnitudes of the candidate object as obtained with the Palomar 20-inch reflector. Horizontal bars indicate the times when spectrograms were obtained with the 200-inch Hale telescope.

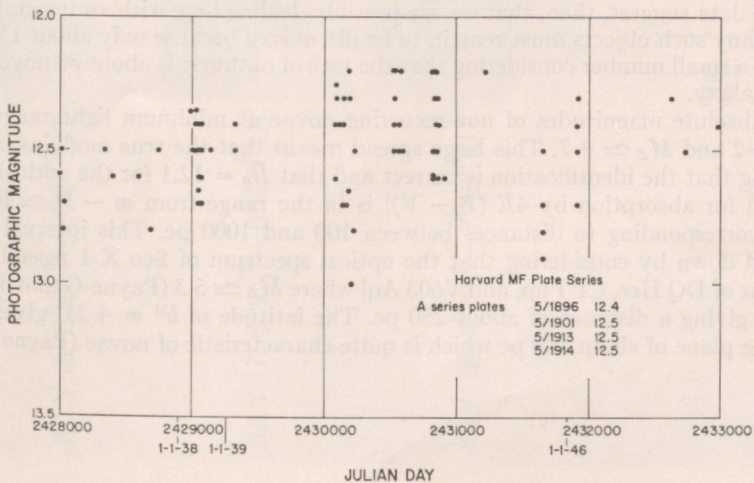


FIG. 3.—Estimates of the magnitude of the candidate object from old plates in the Harvard collection. The zero point and the scale of the photometric system are only approximate.

The spectra taken in the July 13–18 interval were obtained with the 200-inch Hale reflector at a linear dispersion of 85 Å/mm. Many of the plates were taken using the technique of a single trail along a long slit to permit the detection of short period radial velocity changes which Kraft (1963, 1964) has found to be characteristic of old novae and nova-like stars. Figure 4 shows three of the spectrograms taken on July 16, 17, and 18, respectively—nights during which the continuum intensity changes from $\bar{V} \simeq 12.6$ to $\bar{V} \simeq 13.4$ and back again to $\bar{V} \simeq 12.6$. The blank spaces in the individual spectra are time marks made by closing the dark slide of the camera for 2 min while the telescope was trailing the star along the slit.

In general, the spectra are very similar to those of old novae (Humason 1938; McLaughlin 1953; Greenstein 1961; Kraft 1964) in the types of lines present and in their strengths and widths. In particular, the hydrogen lines are in emission, He II is present, and the complex of very high excitation lines probably due to C III, N III, and possibly O II is seen near λ 4650. The interstellar K of Ca II in absorption is clearly seen but the H-line of Ca II is partially masked by H ϵ in emission.

The most striking feature of Figure 4 is the large change in the strength of the Balmer lines between the three nights. These lines are very weak on July 16 and 18 but appear in great strength relative to the continuum on July 17 when the object was very faint. Similar changes occur in DQ Her, MacRae +43° 1 and other old novae (Greenstein and Kraft 1959; Greenstein 1954) and may indicate that the low-excitation Balmer lines are formed in a different region from that in which the variable, blue continuum radiation and the high-excitation lines of He II, N III, and C III originate. This is partially borne out by the relatively small change in the equivalent width (E.W.) of the He II (λ 4686) line on the three nights compared with the large change in H β . Preliminary measurement of microphotometer tracings show that H β had E.W.'s of 0.7, 6.2, and 2.1 Å on the respective three nights while He II (4686) had E.W.'s of 3.6, 2.9 and 2.8 Å.

The most interesting feature is the broad structure between λ 4630 and λ 4655, described before as due to C III, N III, and possible O II. This structure is found in old novae such as V603 Aql (1918), DQ Her, and CP Pup, among others. On our spectrograms the intensity of the structure ranges from almost complete invisibility relative to the He II (4686) line on July 14 to twice the strength of He II on July 18.

We have looked for short-term radial velocity changes which would appear as a characteristic S-wave distortion in the lines on the single trailed spectra. Large changes of this type are known to be characteristic of old novae and nova-like stars (Kraft, *op. cit.*). No changes as obvious as those in DQ Her and WZ Sge (Kraft 1964) occur on our plates but suggestions of an S-wave are present on the July 18 spectrogram for the broad line at λ 4417 and for the H9 + He I + He II line at λ 3836 Å. There are also indications from partially completed measurements that the wavelengths of other emission lines, notably He II (4686), change from night to night.

These data suggest, then, that we are possibly dealing here with an uncatalogued old nova. Many such objects must remain to be discovered because only about 150 are now known—a small number considering that the rate of outburst is about 30 novae per year in our Galaxy.

The absolute magnitudes of non-recurring novae at minimum light range between $M_B \simeq +2$ and $M_B \simeq +7$. This large spread means that the true modulus of Sco X-1 [assuming that the identification is correct and that $\bar{B}_0 = 12.1$ for the optical object as corrected for absorption by $4E(B - V)$] is in the range from $m - M \simeq 10$ to $m - M \simeq 5$ corresponding to distances between 100 and 1000 pc. This interval might be narrowed down by considering that the optical spectrum of Sco X-1 resembles somewhat that of DQ Her, CP Pup, and V603 Aql where $\bar{M}_B \simeq 5.3$ (Payne-Gaposchkin 1957, chap. 1) giving a distance of about 250 pc. The latitude of $b^{\text{II}} = +24^\circ$ gives a height above the plane of about 100 pc which is quite characteristic of novae (Payne-Gaposch-

1966
JULY 16 5^h21^m–8^h21^mUT

JULY 17 5^h10^m–8^h27^mUT

JULY 18 4^h18^m–7^h18^mUT

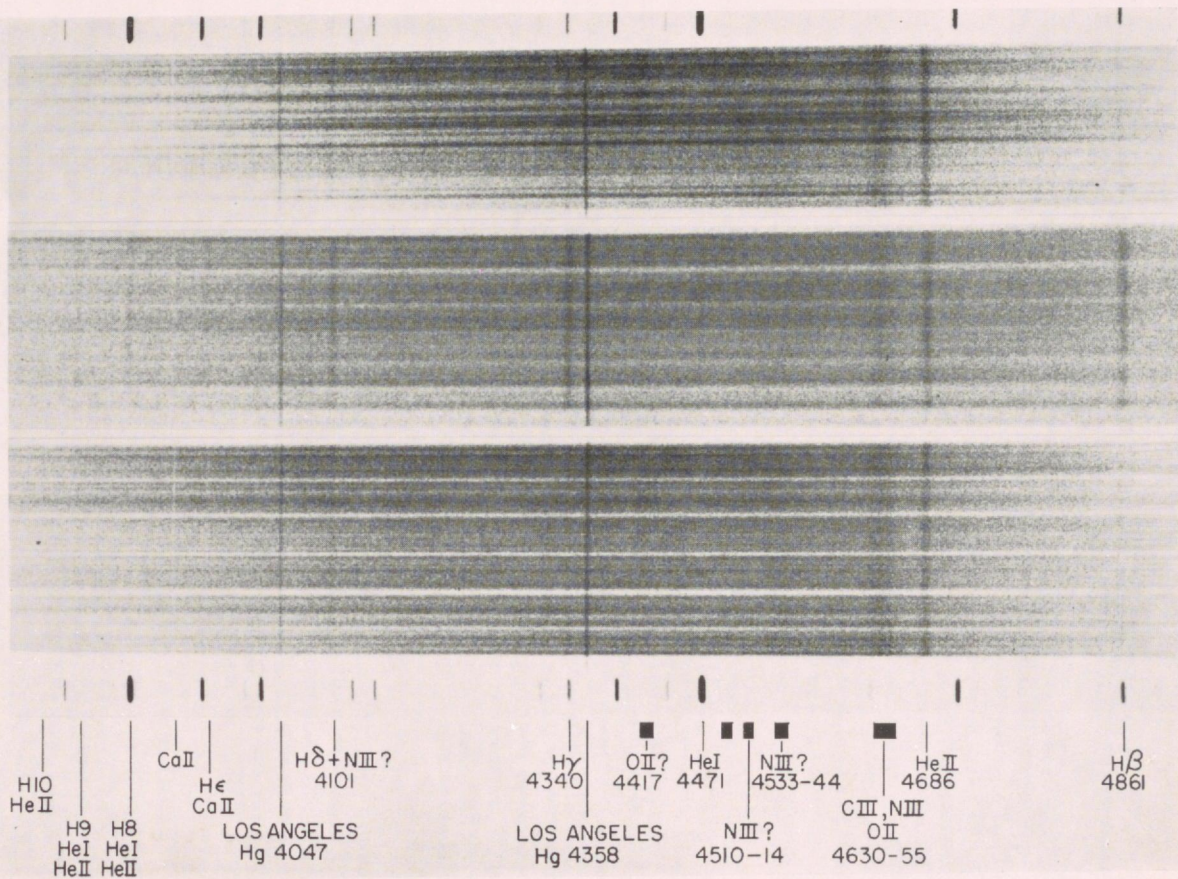


FIG. 4.—Three continuously trailed spectra in the blue spectral region. Time marks, made by closing the camera dark slide, are evident on the last two. Tentative line identifications are indicated. The comparison arc is He. The original dispersion was 85 Å/mm.

kin 1957, Table 2.4). It should be emphasized that this quoted value of the distance is strictly a consequence of the assumption that Sco X-1 is in fact a nova, and, of course, we have no definite proof that this is indeed the case.

We believe that we have identified the visual counterpart of the X-ray source Sco X-1. This object appears to have certain of the properties of an old nova even though its spectral characteristics cannot be identified with any one class of old novae. The most striking characteristic of the object is that it emits X-rays in copious quantity. The energy emitted in the 1–10 Å region is about one thousand times greater than that emitted in visible light. The observed visual magnitude is close to the value computed by extrapolating the energy distribution from the observed range of 1–10 Å into the optical region with the exponential spectrum of bremsstrahlung emission from an optically thin gas. This implies that the bulk of the observed emission in the visible light continuum can be accounted for by the process which we have assumed to give rise to the observed X-rays. If this is so, then we may be able to observe fluctuations in the X-ray emission correlated in time with the fluctuations in the visible continuum.

We shall not attempt here to discuss the physics of this system any further except to note that the objects which are categorized as old novae appear to possess disk structures which emit variable, blue continuous radiation by optical bremsstrahlung and by bound-free transitions of H and He. The excitation mechanism and the kinetic temperature of the gas is unknown. If, in this particular object, parts of the gas have $T \simeq 5 \times 10^7$ ° K, the bremsstrahlung process could produce the observed X-rays. We do not yet know if all old novae are X-ray sources at some power level. It may be that only a fraction of these explosive stars have kinetic temperatures in their external gaseous component which are high enough to emit X-radiation. The distribution of known old novae is consistent with the general distribution of other known X-ray sources (Bowyer, Byram, Chubb, and Friedman, 1965). A two-color optical survey is now in progress with the 48-inch Palomar Schmidt telescope to attempt detection of other blue objects which might be associated with the presently known X-ray sources.

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