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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 1966*a*). 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.* (1966*b*) 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^h15^m and 16^h and 18^m. An ultraviolet and a blue image of each star was obtained through a Hoya U2 filter ($\lambda \simeq 3600$ Å) and a

Hoya L-39 filter ($\bar{\lambda} \simeq 4400$ Å). 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 Å/mm at 4000 Å and 150 Å/mm at Hβ. The spectrum, which was underexposed because of unfavorable sky conditions, showed a continuum with no absorption features and with faint emission at Hγ and λ 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 Hβ, He II (λ4686), Hγ, Hδ, and possibly Hϵ 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 α (1950) = $16^h17^m4.3^s$, δ(1950) = $-15°31'13''$. 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 $\pm \frac{1}{2}°$ 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 $(m - M)_{\rm true}$ 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.

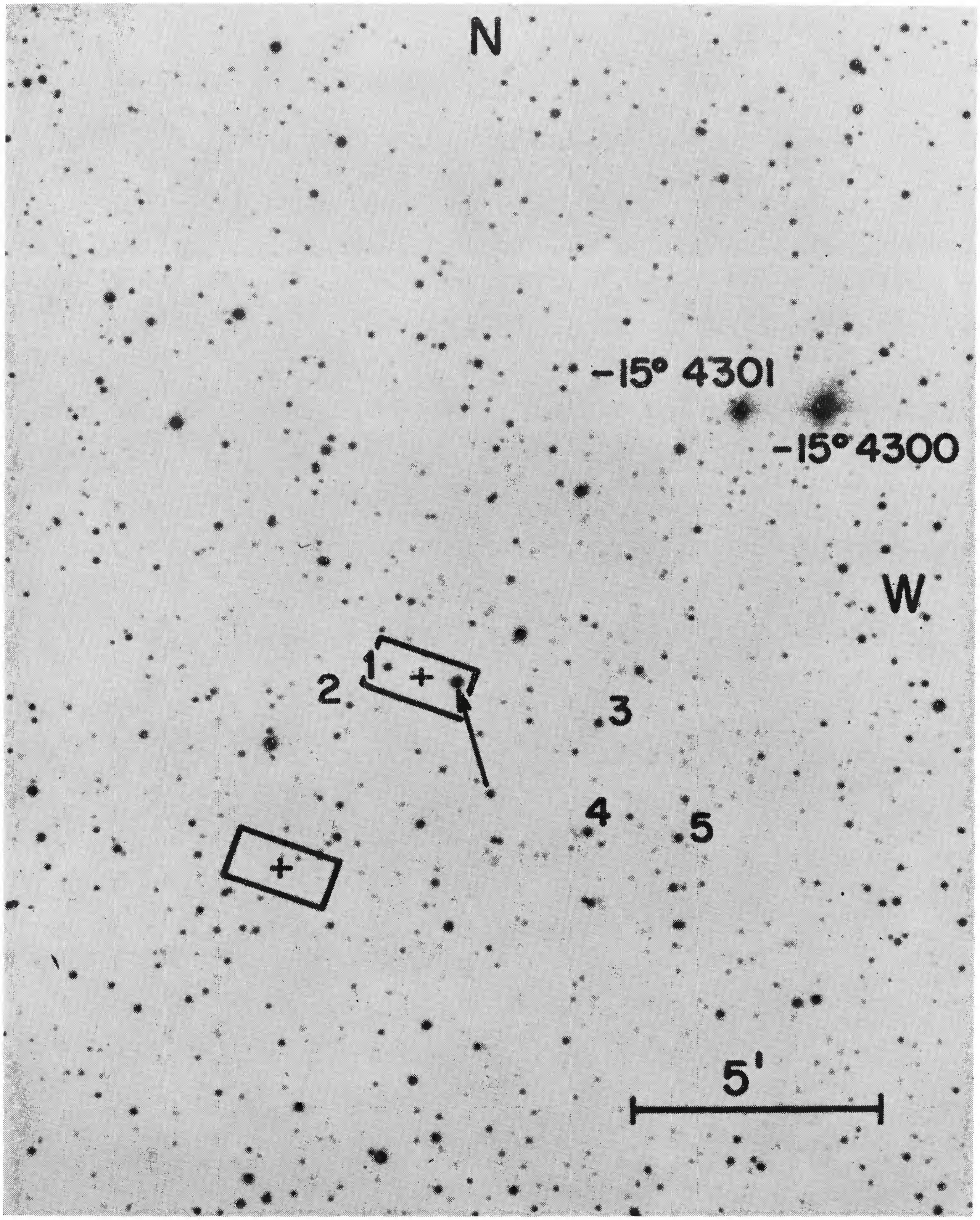

FIG. 1.—Photograph of the region containing the new X-ray position of Sco X-1, reproduced from the Palomar Sky Survey prints. The two equally probable X-ray positions are marked by crosses surrounded by a rectangle of 1 by 2 arc min. The object described in the text is marked with an arrow. The identifications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

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 (λλ 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	$B-V$	$U-B$	$E(B-V)$	$(m-M)_{app}$	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	
Sco X-1	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	...	...	
	...	...	...	...	...	
	13 01	0 21	− .76	...	...	July 12 U.T., 1966 data over a time interval 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.

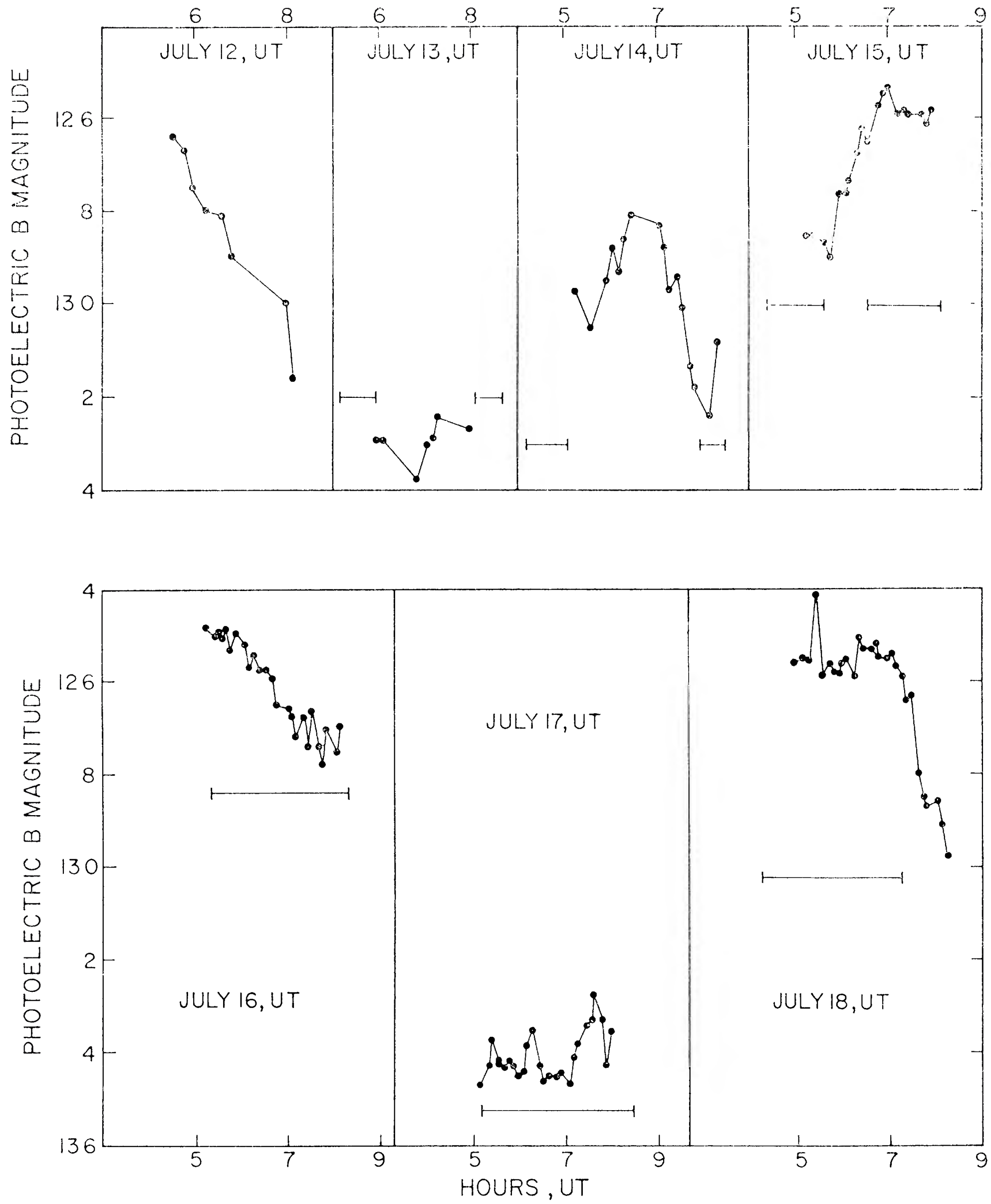

FIG. 2.—Photoelectric *B* magnitudes of the candidate object as obtained with the Palomar 20-inch reflector. Horizontal bars indicate the times when spectrograms were obtained with the 200-inch Hale telescope.

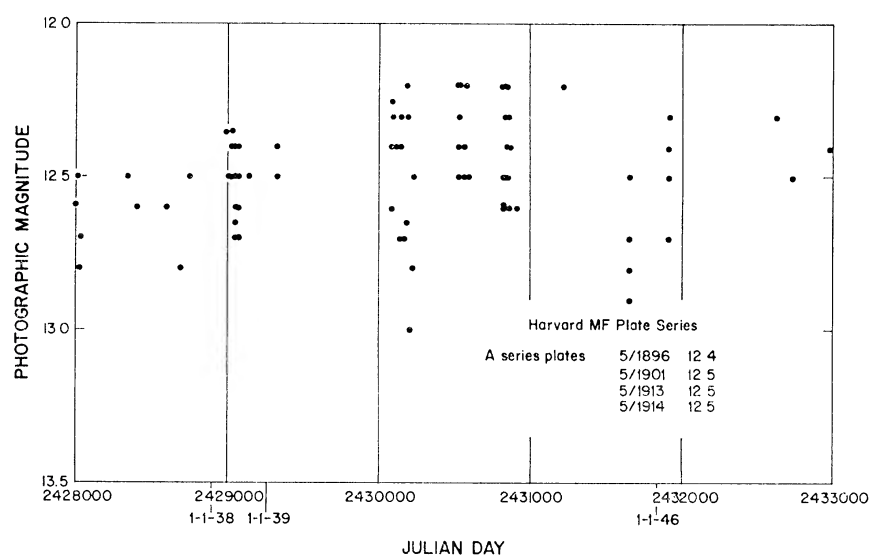

FIG. 3.—Estimates of the magnitude of the candidate object from old plates in the Harvard collection. The zero point and the scale of the photometric system are only approximate.

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 Hϵ 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 D Q 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 Hβ. Preliminary measurement of microphotometer tracings show that Hβ 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 A. 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 $b^{\text{II}} = +24°$ gives a height above the plane of about 100 pc which is quite characteristic of novae (Payne-Gaposch-

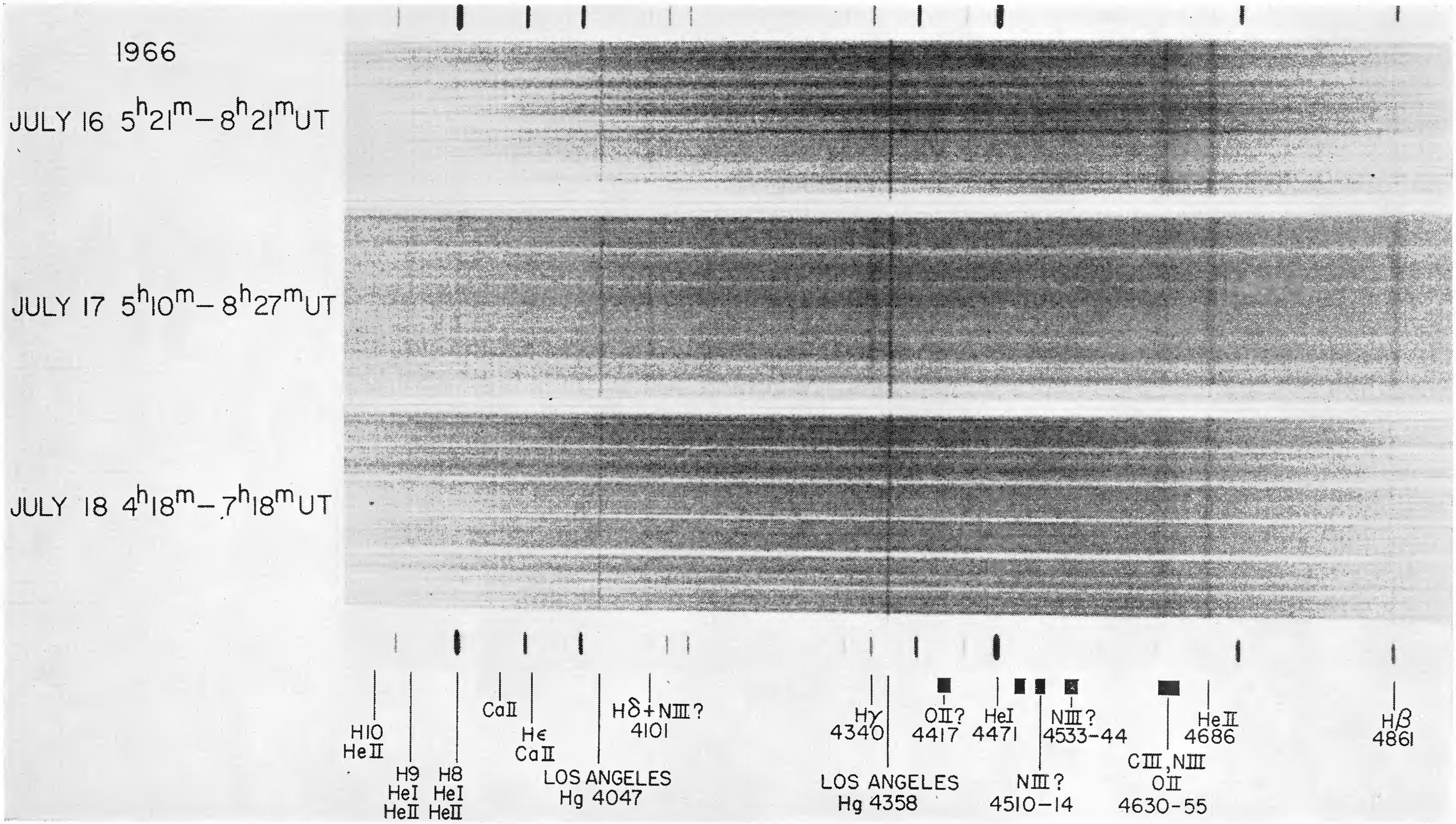

FIG. 4.—Three continuously trailed spectra in the blue spectral region. Time marks, made by closing the camera dark slide, are evident on the last two. Tentative line identifications are indicated. The comparison arc is He. The original dispersion was 85 Å/mm.

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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