NON-SOLAR GAMMA AND X-RAY ASTRONOMY: OPTICAL OBSERVATIONS*

(Invited Discourse)

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An optical astronomer enters this field only by courtesy of those X-ray astronomers who pay some attention to accurate positional measurements of X-ray sources. So my first and last words are to ask X-ray observers to give more time to establishing positions of X-ray sources. It appears that in fact most effort has been spent on spectral measurements of X-rays, and this has led just to the classification of sources according to either of two mechanisms for the production of the continuum. In one or two early instances the extrapolated X-ray spectrum has been useful for predicting the brightness of the optical counterpart to be found. A typical uncertainty of making optical identification is that of Vel XR-1 for which Gursky *et al.* (1968) have given a position with an error box of 3 square degrees. One candidate I can suggest for this is CU Vel, the only variable star of the 1958 *General Catalogue of Variable Stars* inside the error box. It is interesting because it is assigned to the U Gem class with a range of photographic magnitudes from 10.7 to 15.5. The stellar spectrum has not been observed.

The optical light of identified sources may arise in another volume than the very energetic plasma which emits the X-rays. But we can hardly doubt that the various parts of an X-ray source interact. In this sense X-ray sources were first known to be certainly variable as soon as Sco X-1 was identified with a variable star. Much effort has been spent to observe the optical variability of Sco X-1 independently of X-ray observations. Periodicity has been especially sought, for it would lead to a great advance in understanding the source whether the periodic light curve arose from orbital or pulsational modes. Optical tests for periods in the range from 2 sec to many hours have been made on Sco X-1. Ephemeral or quasi-periodical effects have been suspected, e.g. at 0.5276 day (Van Genderen, 1969).

It is still impossible to conclude on the basis of photometric observations that either Sco X-1 or any other X-ray source is a binary or a pulsating star. However, the only known optical pulsar has been found in the Crab nebula, and the pulse is present in the X-radiation. It becomes interesting to look for short periods in other X-ray sources, although we have no guiding theory as to whether most X-ray sources can develop or maintain pulsar characteristics. J. C. Golson and I at Kitt Peak National Observatory have reached a preliminary negative result against periodicities down to

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0.002 sec for Sco X-1. To do this we have used a stroboscope which interrupts the beam of a star into a conventional d.c. photometer. The stroboscope was constructed with the aid of A. J. Gardiner at the Kitt Peak National Observatory in accordance with our rough plan. The stroboscopic frequencies can be increased steadily from zero to 500 sec^{-1} for several minutes. We have used *u*, *b*, *v*, *y* filters as well as no filters over the 1P21 photomultiplier. The recorder graph of the amplified current output on March 27 and April 12, 1969, shows about the same noise whether the stroboscope is running or the beam is passed without interruption (Figure 1). Laboratory tests of

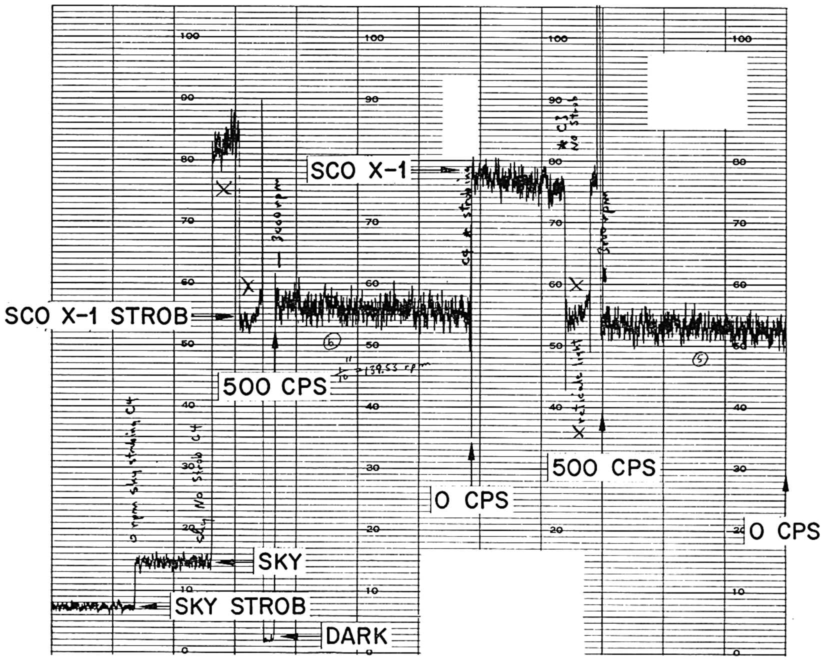

Fig. 1. Recorder chart from April 12, 1969, of the d.c. output of an unfiltered 1P21 photomultiplier, showing response to light of Sco X-1 governed by a stroboscope running at pass-stop frequencies which rise steadily from zero to 500 sec^{-1}. No resonances are apparent.

the stroboscope on a.c. lamps confirm during similar frequency scans that, when the stroboscopic period or multiple of it approximates to the period of the lamp, the amplitude of the recorder graph becomes very great compared with random-noise fluctuations. Although we do not see such resonances in any of the records of Sco X-1, we can refine this first application and also extend the technique to some other objects.

Narrow-band photometry can concentrate on selected lines in the optical spectra of identified X-ray sources. Figures 2, 3, and 4 show narrow-band observations of WX Cen, the nucleus of NGC 5189, and the object called GX3+1. The first two of these three objects are rival candidates for the identification of Cen XR-2. The pass-bands are specified in Figure 5 and Table I. The 60-inch reflector of the Cerro Tololo Inter-American Observatory was used on April 8–12, 1969, UT, and the 36-inch on

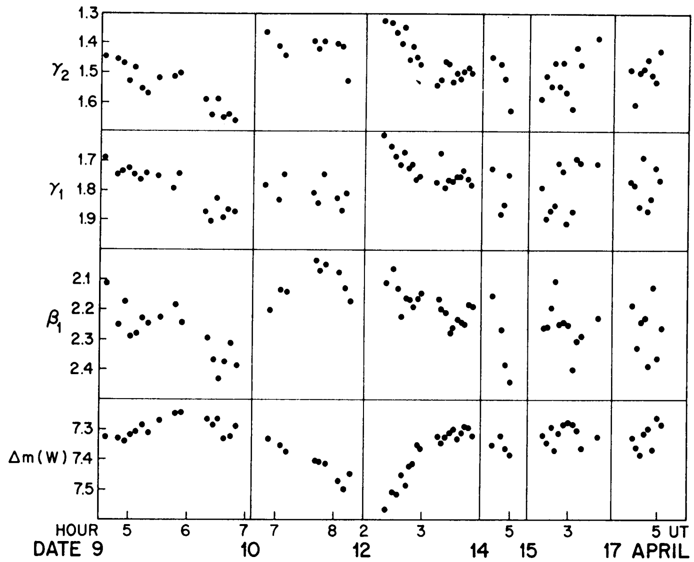

Fig. 2. Light curves of WX Cen in $\Delta m(W) = m$(wide Hβ) (object) – m (wide Hβ) (comparison star), in $\beta_1 = m$ (narrow Hβ) – m (wide Hβ), in $\gamma_1 = m$ (narrow λ4648) – m (wide λ4694), and in $\gamma_2 = m$ (narrow λ4684) – m (wide λ4694). The comparison star is HD 114461, type F0, $m_{pg} = 6.9$.

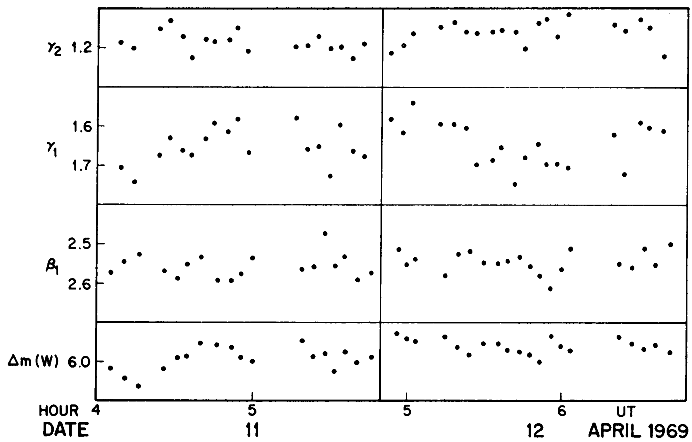

Fig. 3. Light curves of the central star of NGC 5189 as in Figure 2. The comparison star is HD 117694, type B9, $m_{pg} = 8.8$.

April 13–17, for the work. The integration time per filter was always 20 sec except on April 9. The corresponding start-to-stop times were 20 sec for $m(W)$, 85 sec for β_1 and γ_2, and 130 sec for γ_1, where β_1, γ_1, and γ_2 are composed of pairs of integrations with narrower-band filters centered on single wider-band integrations. On April 9 the integration time per filter was 30 sec and start-to-stop times were 30 sec for $m(W)$, 110 sec for β_1 and γ_2, and 180 sec for γ_1. The reductions assume a linear change of the light between the first and last integrations of each plotted datum. In short, the

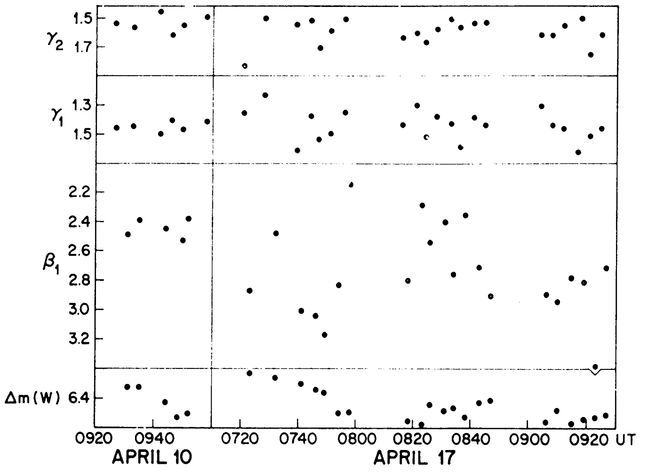

Fig. 4. Light curves of GX3 + 1 as in Figure 2. The comparison star is HD 160972, type A5, $m_{pg} = 8.6$.

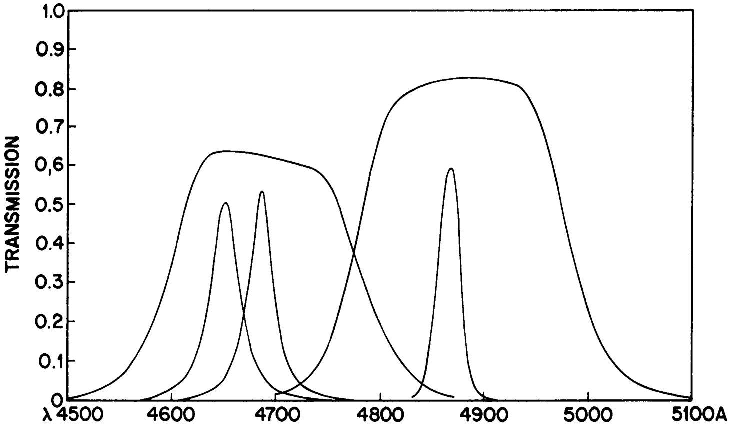

Fig. 5. Passbands used to observe X-ray sources at Cerro Tololo Inter-American Observatory in April, 1969. The wide and narrow bands around Hβ give, respectively, $m(W)$ and $m(N)$, while $\beta_1 = m(N)$–$m(W)$ is a measure of the strength of Hβ. According to the areas under these curves $\beta_1(0) = 2.531$ magnitude corresponds to null Hβ. The other narrow bands transmit C III, N III 4640 and He II 4686, respectively, while the wide band over them serves with them to give an index γ_1 of the equivalent width of λ 4640 and an index γ_2 of the equivalent width of λ 4686. The laboratory value for null λ 4640 is $\gamma_1(0) = 1.812$ magnitude, and for null λ 4686 it is $\gamma_2(0) = 1.954$ magnitude.

methods are much the same as in the first of a series of narrow-band photometry by Johnson and Golson (1968a). The filter set used at Cerro Tololo is different from the set used in the beginning of the series, but the significance of $\Delta m(W)$ is very nearly the same as it was then. The Hβ index differs from the β' of previous reports simply in scale and zero-point; γ_1 and γ_2 distinguish narrow emissions around λ4640 and λ4686 which were passed together under a filter which we previously had used for them.

TABLE I

Photometric passband characteristics of equipment used at the Cerro Tololo Inter-American Observatory

Filters No.	λ_{eff}(A)	Equivalent width (A)	Transmission at lines	Spectral features
387	4648	22.8	0.42	N III 4634–41, C III 4647–51
406	4684	20.0	0.51	He II 4686
407	4694	121	0.63	N III, C III, He II
217	4865	17.4	0.57	Hβ (narrow)
222	4880	179	0.82	Hβ (wide)

The separation is incomplete, of course, for very broad and blended $\lambda\lambda$4640–4686. The rms errors in this work may be estimated from the rms error of the β_1 measurements of the comparison stars of the three objects to be discussed. This error is ± 0.007 mag.

The principal features of the blue spectrum of WX Cen are Hβ, He II 4686, and N III, C III 4640. The lines are broadened but the λ 4640 feature is partially resolved from the dominant He II 4686 (Eggen *et al.*, 1968). According to the Cerro Tololo photometry there is on some, but not on all, days a correlation between the continuum as represented by $\Delta m(W)$ and the line indices in the sense that, as the continuum brightens, the equivalent width of any of the observed emission features decreases. Keeping all of the data there is apparently a positive correlation between γ_1 and γ_2, and between β_1 and γ_2. The index γ_1 is well correlated with γ_2 and β_1 on April 9 and April 12, but it has distinctly dropped in relative brightness on the 10th. The times of the β_1 data lag about 3 min behind the times of the γ_1, γ_2 data, but this may have little effect within the time scale of the major variability. WX Cen certainly varies within an hour and probably within a few minutes, but 'flaring' is not clearly present. These data could result from a volume of slightly variable line fluxes in the presence of a more highly variable continuum flux.

The blue spectrum of the central star of NGC 5189 apparently shows very strong, broad emissions of O VI 3811–34, and He II probably partially blended with C III, N III 4640 (Blanco *et al.*, 1968). Hβ is not contained on the published spectrogram. The present narrow-band photometry of the central star was done with a diaphragm of 10″ diameter. If the light of the nebula is distributed in the photographic region like that of the central star, and also uniformly over its surface, about 15% of the total light passed by the diaphragm is estimated to be nebular. However, the relative contribution of the nebular lines in the filters of Table I is probably much less than the estimate suggests, and the light curves of Figure 3 should pertain quite well to the central star. There is some correlation between $\Delta m(W)$ and β_1 of the same sense as in WX Cen, and the quality of variability in these light curves resembles that of WX Cen. However, $\langle\beta_1\rangle > \beta_1(0) = 2.531$ magnitude (the value of computed null equivalent width of Hβ), and this implies net absorption rather than net emission close to Hβ. A similar effect in GX3+1 is mentioned below. Also, the variations of γ_1 and γ_2 are definitely not so well correlated in the central star of NGC 5189 as the variations of these indices are in WX Cen. The mean values of γ_1 and γ_2 show that the complex of emissions around $\lambda\lambda$ 4640–4686 has greater equivalent width in the spectrum of the central star of NGC 5189 than in the spectrum of WX Cen.

The spectrum of the ultraviolet object in Sagittarius, identified with the X-ray source GX3+1, is similar to that of the central star of NGC 5189 but with even greater broadening and blending of emission features (Blanco *et al.*, 1968; Freeman *et al.*, 1968). Figure 4 shows variability of GX3+1 in $\Delta m(W)$ much as in an earlier report (Johnson and Golson, 1968b), and β_1 again goes through a large and erratic dispersion as did β' in 1968. The mean of β_1 mimics an absorption-line at Hβ. As in 1968, this may represent the net gap between broad emission wings of He II 4686 and O V 4925–40. Emissions of probably C III, N III, and He II blend and spread over our narrow passbands (and indeed fill much of the wider passband of the system) which make up the indices γ_1 and γ_2. These gross effects on the passbands must alter the meaning of the absolute values of γ_1 and γ_2 from the meaning they would have for narrow lines. We can still say that their magnitudes show that the mean ratio of the equivalent widths of λ 4640/λ 4686 is greater in GX3+1 than it is in the central star of NGC 5189; again the variability of γ_1 and γ_2 is apparently uncorrelated.

If the emitting volumes of X-rays and optical radiation interact in X-ray sources, we ought to look for correlations in the variability by taking simultaneous data in two or more *wide-spaced* passbands. The most spectacular of the light variations of Sco X-1, the so-called 'flares', have escaped such inspection. But on four instants measurements of flux density in the range 2–20 keV have been made from rockets while a ground-based astronomer cooperatively observed Sco X-1 in *UBV* (Mark *et al.*, 1969). The four pairs of flux-density data have been analyzed by these authors to derive some physical properties of Sco X-1 which could not be approached by means of X-ray data alone, namely plasma volume radius (about 10^9 cm) and density (about 10^{16} cm^{-3}), but the correlation between variations of radius, density, and temperature is not clear from these data. Sco X-1 has been observed on May 22, 1968, with balloon-borne detectors working at 20–40 keV, and simultaneously with the 84-inch reflector at Kitt Peak National Observatory (Pelling *et al.*, 1969). The X-ray flux then appeared to vary less than a 25% slow rise and fall of the continuum around Hβ during a period of several hours. At the same time Hβ emission and the emissions around $\lambda\lambda$ 4640–4686 also varied little compared with variation in the continuum. A full report will be published elsewhere. Sco X-1 has also been observed by B. H. Andrew and C. R. Purton at the Algonquin Radio Observatory at 4.6 cm for several hours on April 14, 1969, and by me simultaneously at Cerro Tololo Inter-American Observatory in a first attempt to correlate radio and optical variability. The data are not reduced in time for this Symposium.

In short, simultaneous X-ray/optical/radio photometry of variable X-ray sources has been undertaken only for Sco X-1, and the data still cannot all be correlated in terms of simple models. The characteristics of *UBV* (broadband) variability of Sco X-1 are sufficient to suggest that the optical continuum of Sco X-1 is optically thick (Johnson, 1968a). The slope of the spectrum of Sco X-1 from the visible to 2.2 μ also suggests an infrared-dominant blackbody in Sco X-1 (Neugebauer *et al.*, 1969). These results agree with the models of Mark *et al.* (1969), the ones derived partly from X-ray data. But the radiofrequency data of Andrew and Purton (1968) and Ables (1969) cannot be accommodated in such pictures of Sco X-1. The radio data may require a basically two-component model, of which the one contributes soft X-rays and the other identifies perhaps with the optical line-emitting cool-gas component (Riegler and Ramaty, 1969).

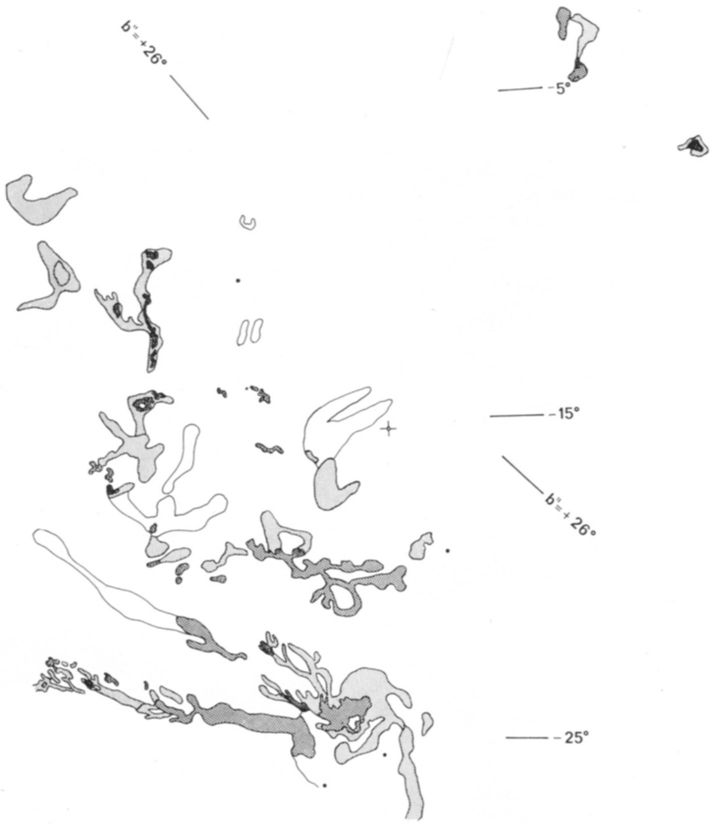

Fig. 6. Dark nebulae around Sco X-1 (cross mark). The darkest clouds are given the blackest shading. Compare with Lynds (1962) for a map of the larger area which shows the unusual aspect of these clouds in relation to the general obscuration in the Milky Way.

No *characteristic* X-rays have been found in cosmic sources other than the sun. Thus the optical line spectrum of X-ray sources is the only present means of making radial-velocity measurements or abundance analyses of them. Not much progress has actually been made because of the complex behavior of the few available radial velocities of Sco X-1 and Cyg X-2, the very great breadth of the lines in some other sources, and, in respect to standard abundance analyses, doubts about applicability to such anomalous objects. We can only reinforce the negative photometric conclusion on the subject of periodic binary or pulsational motions, and note the weakness or absence of Balmer lines as compared with the strength of helium in some sources such as GX3+1 which are like Wolf-Rayet stars.

All model-making starts with the distance of a source. Because the earliest proper-

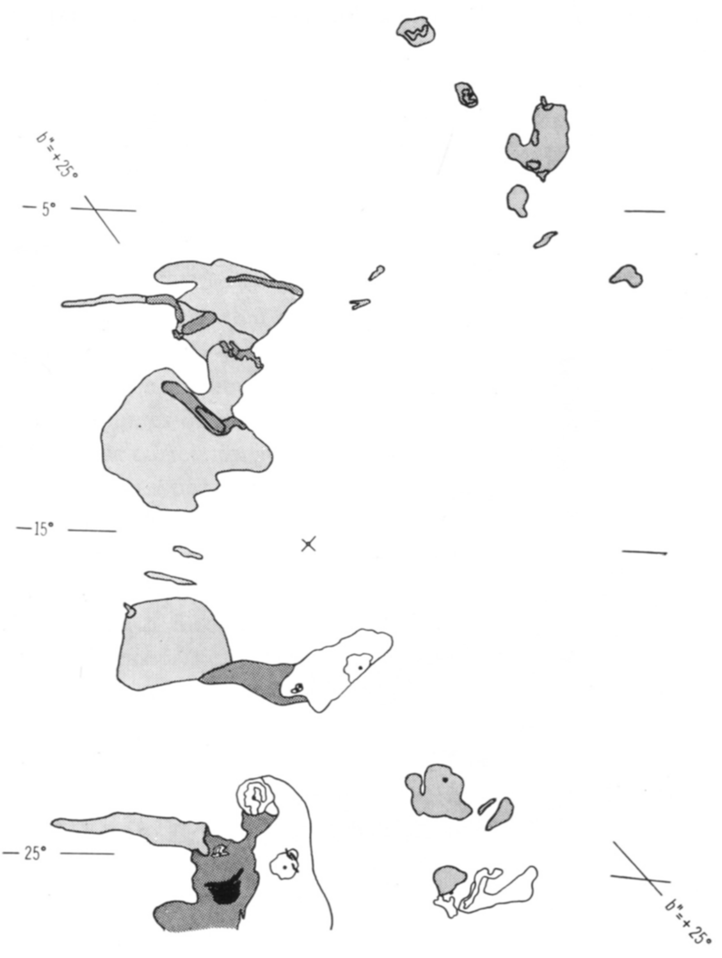

Fig. 7. Luminous nebulae around Sco X-1 (cross mark). The nebulae which are brighter on the blue than on the red Palomar Sky Survey are unshaded. Nebulae that appear red are shaded; the degree of shading is supposed to represent the brightness of the nebulae.

motion measurements of Sco X-1 (Johnson and Stephenson, 1966; Luyten, 1966) included mean errors of about $\pm 0\overset{''}{.}017$ – larger than the proper motions – it has been concluded by Luyten and later by others that Sco X-1 is very distant. Now Sofia *et al.* (1969) have determined the proper motion of Sco X-1 with greater accuracy, i.e. with mean errors of $\pm 0\farcs0022$, and the proper motion agrees with the proper motions of members of the Sco-Cen association. The conclusion is that Sco X-1 is most probably at the distance of the association, 170 psc according to Bertiau (1958), and that it belongs to a strong population I group. Several years ago I suggested (Johnson, 1966) that Sco X-1 is in the Sco-Cen association because it appeared to be centered in arc-like distortions of the interstellar dust clouds which Lynds (1962) had mapped before the discovery of Sco X-1. If Sco X-1 is immersed in interstellar clouds, we must ask whether the current radiation of Sco X-1 affects them. This inquiry may be applied to the strength of interstellar Ca II K, which Wallerstein (1967) has found to be unusually great in the spectra of Sco X-1 and in HD 146935, a star separated 10′ from Sco X-1 on the sky, in comparison with the strength of Ca II K in stars somewhat farther from Sco X-1. However, here we ask whether any of the red interstellar clouds in the vicinity

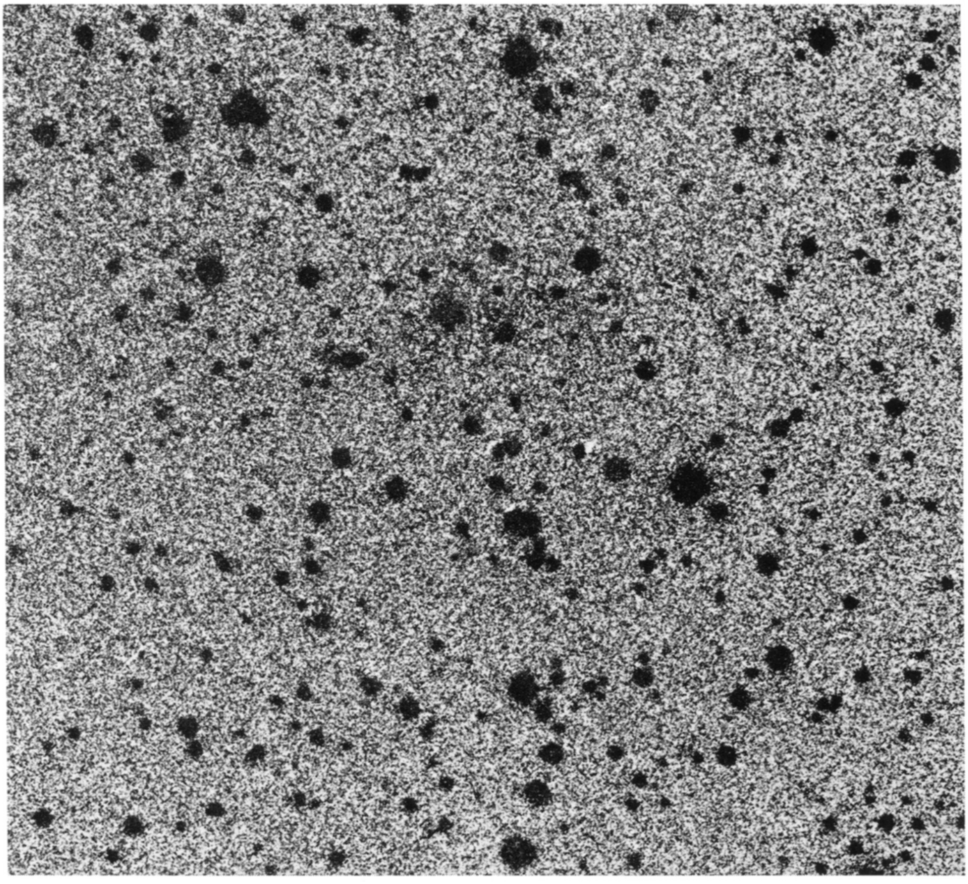

Fig. 8. An area of 8′ × 9′ centered on Cas A. A diffuse arc of radius 2′ may be seen in the northern quadrant above center (East to the left). It is apparently the optical continuum of the supernova remnant in the passband $\lambda\lambda$ 5200–6300. The high-contrast print on Kodalith Ortho paper was made from a sandwich of Kodalith Ortho film copies of two plates exposed in the 48-inch Schmidt telescope on May 6 and 7, 1967.

of Sco X-1, found on the Palomar Sky Survey and catalogued by Mrs. Lynds (1965), are radiating in Hα or are scattering the light of a red star. This is a future observational problem. We must also discover whether the radiation of Sco X-1 contributes to the photoionization of the neighboring red clouds. Ultimately new information about the spectrum of Sco X-1 below 912 Å may be obtained starting from its site in interstellar matter. Figures 6 and 7, respectively, are maps of dark and luminous clouds near Sco X-1 prepared by Mrs. Lynds. Regarding the history of interstellar matter around Sco X-1, I note that the proper motion of ζ Oph is roughly equal in magnitude and opposite to that of Sco X-1. ζ Oph is a 'runaway' O star in the Sco-Cen association. The high speed may reflect a supernova event (Blaauw, 1961).

Optical observations of known supernova remnants may be as relevant to X-ray astronomy as to radio astronomy, but the material is too extensive for review here. The principal thing to note is that parts of supernova remnants may fluoresce in the optical band because they are supplied with photons below 912 Å. Optical variability may lead to information about the stability of XUV sources in supernova remnants. The optical continuum of the Crab nebula is observed to be much stronger than possible optical continua in other supernova remnants. Figure 8 illustrates an attempt to photograph the yellow continuum of the Cas A synchrotron continuum (Johnson, 1968b). A photoelectric observation by J. C. Golson and me at Kitt Peak National Observatory in November, 1968, apparently confirms this continuum. The observation is the first epoch in a series intended to monitor long-term variability of [O III] 5007 and the continuum in Cas A. The Crab nebula is similarly monitored. The whole subject of the effects of XUV-source radiation on the interstellar environment deserves theoretical and observational effort.

Acknowledgements

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