ASE-1408

ANALYSIS OF SOUNDING ROCKET DATA
[illegible] CELESTIAL X-RAY SOURCES

PREPARED UNDER CONTRACT NO. [illegible]

AMERICAN SCIENCE AND ENGINEERING, INC.

11 CARLETON STREET, CAMBRIDGE, [illegible]

FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ASE-1408

ANALYSIS OF SOUNDING ROCKET DATA REGARDING CELESTIAL X-RAY SOURCES

By H. Gursky, R. Giacconi, P. Gorenstein and J. R. Waters

Prepared under Contract No. NASw-1396 by
AMERICAN SCIENCE AND ENGINEERING, INC.
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for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

This document is the final report on Contract NASw-1396, which called for the reduction and analysis of data obtained from the flight of a sounding rocket containing an instrumented payload (developed by AS&E) designed to study the celestial X-ray sources with high angular resolution.

ACKNOWLEDGEMENTS

We wish to acknowledge the support in this work of Mr. G. Ouellette who was responsible for many of the astronomical calculations presented here, Mr. M. Bate, who was responsible for the computer programming effort and Mrs. J. Zmijewski, and Miss T. Arczynski, who did most of the data scanning and the computational work.

Part of this work represented a joint effort with scientists at several institutions. The individuals involved were: Professor H. Bradt, Professor G. Garmire and Dr. B. V. Sreekantan of MIT; Professor M. Oda, K. Osawa, and J. Jugaku of Tokyo University and Professor A. Sandage and P. Osmer of the Mt. Wilson and Palomar Observatories.

We wish also to acknowledge many fruitful discussions with Dr. M. Annis, Dr. J. Carpenter, Dr. S. Frankenthal and Dr. O. Manley of AS&E; Professor Bruno Rossi and Professor B. Burke of MIT and Professor Margaret Burbridge of the University of California at San Diego.

INTRODUCTION

On the basis of the work performed under this contract, we have been able to make an identification of the visible counterpart of ScoX-1, the strong X-ray source in Scorpio. As had been predicted from an analysis of the rocket data, the object is blue and of 12th magnitude. It has many of the characteristics of an old novae; its spectrum shows hydrogen and helium emission lines as well as high excitation lines of carbon, nitrogen and oxygen superimposed on the continuum radiation. The spectrum shows no absorption features. The light output (both continuum and line emission) show irregular variations of as much as 1 magnitude per night.

The identification was made possible by the observation of ScoX-1 with X-ray instruments that were qualitatively different from any previously used in sounding rocket experiments. The angular resolution of the collimators was about 40" and an aspect measuring system was employed that largely eliminated the possibility of systematic errors in location resulting from alignment errors. (The hardware and the general experiment techniques are described in ASE document 1372, the final report on NASw-1396). As a result we were able to set an upper limit of 20" to the angular size of the X-ray emitting region and to measure the location of the source with a precision of about 1 arc minute.

The significance of this identification is that now the full potential of ground-based observatories can be utilized to study the object in as much detail as is necessary. Furthermore, it is likely that ScoX-1 is typical of the remaining X-ray sources, including those associated with supernova remnants. In this respect it should be noted, that in spite of the fact that the Crab Nebula (which is perhaps one of the most carefully studied objects in the sky) has been identified as an X-ray emitter for three years, there is still no satisfactory explanation of its X-ray emission. In the Crab Nebula, the visible light results from physical processes that cannot be directly related to the X-ray emission; in ScoX-1, on the other hand, the intensity of the visible light output is within a factor of two of the lower limit predicted on the basis of the X-ray emission. Thus in visible light, one is studying the X-ray production process almost directly.

The region was also scanned for a radio source by Professor Bernard Burke of MIT using the Haystack Facility of Lincoln Laboratories. No significant flux was found and an upper limit of 0.5×10^{-26} watts/cm^2-($^c/s$) was set for any possible source. The predicted lower limit in radio for ScoX-1 on the basis of its visible and X-ray emission is two orders of magnitude below this value.

The results are described in detail in four papers included as part of this report. Appendix A describes the determination of the angular size of the X-ray source, Appendix C describes the position determination and Appendix D describes the visible counterpart. Appendix B is a theoretical paper by Dr. O. Manley of AS&E that describes some of the implications of the experimental results on ScoX-1 that we have obtained. These papers have appeared or are scheduled for appearance in the Astrophysical Journal.

THIS ANALYTIC NOT USED DUE TO POOR QUALITY.

drift about the specified directions by ±0°.5 at a rate of a few arc minutes per second of time. The attitude of the rocket was obtained by photographing the star field at 1-sec intervals. The central axis of the camera was approximately aligned with the collimator axis. The images of fiducial lights that reference the transmission bands of the X-ray collimators to the star field were simultaneously recorded. Ultimately we hope to derive from these photographs and the counter data the celestial location of the X-ray sources to better than 1′.

In the current experiment we devoted the entire available time to the observation of two X-ray sources, Sco X-1 and the Crab Nebula. The source Sco X-1 was first seen by Giacconi, Gursky, Paolini, and Rossi (1962). It was subsequently observed by Gursky, Giacconi, Paolini, and Rossi (1963) and by Bowyer, Byram, Chubb, and Friedman (1964*a*) and on several occasions by various groups since then. The existence of an X-ray source with an angular size of about 1′ in the Crab Nebula was reported by Bowyer *et al.* (1964*b*), who observed its occultation by the Moon during a rocket flight. In order to point the instrument to Sco X-1 we combined the results of Clark, Garmire, Oda, Wada, Giacconi, Gursky, and Waters (1965) and Fisher, Johnson, Jordan, Meyerott, and Acton (1966) to obtain a location for Sco X-1 of R.A. 16^h15^m and decl. −15°.6.

The results reported here are based on data obtained between 290 and 302 sec after launch, while Sco X-1 was within the field of view of the collimator. The photograph taken at 295 sec shown in Figure 2, shows that the collimator axis was about 3° from Sco X-1. The counter data, shown in Figure 3, consist of the actual number of those pulses corresponding to an energy deposition of less than 15 keV, accumulated per 0.05 sec. When plotted as a function of time, the data show a series of peaks caused by the slow drift of the collimator axis across the source region. Each peak occurs when the X-ray source is aligned with one of the transmission bands of the collimators. Comparing the observed width and shape of the peaks (after applying a dead time correction of 0.5 msec) with the estimated response to parallel radiation, we conclude that the angular size of the source along the scan direction must be less than 20″.

The upper limit on the angular size of Sco X-1 found in the present observation has important implications as to the nature and physical characteristics of the emitting object. We have here considered only some of the more immediate consequences; additional considerations are presented by Manley (1966) in an accompanying paper in which a new model for celestial X-ray sources is also introduced.

In the first place, we note that the observed upper limit on the angular size is incompatible with the hypothesis proposed by Oda (1963) and by Shklovskii (1965) according to which Sco X-1 would be the remnant of an ancient and relatively nearby supernova whose central core has expanded to several arc minutes so that its surface brightness in visible light has fallen below the limit of detectability.

In the second place, we consider the implications for models based on emission from a hot plasma (Heiles 1964; Burbidge, Gould, and Tucker 1965; Morrison and Sartori 1965) possibly associated with supernova remnants. Supernova remnants (e.g., Crab Nebula) are observed to expand with velocities of the order of 1000 km $\sec^{-1}$, and a hot plasma at the temperature required to give the observed X-ray flux should expand with a comparable velocity. Using as a measure of age of the object, τ, its present linear diameter divided by the expansion velocity (taken as 1000 km $\sec^{-1}$), we derive the relationship

$$\tau = 2.5 \times 10^{-3} \delta R \text{ years}, \qquad (1)$$

where δ is the angular diameter in arc seconds and R is the distance to the source in parsecs. If we use the measured upper limit of 20″ for the object, and we assume, as suggested by the relatively great intensity and high galactic latitude of Sco X-1, that it is closer than the Crab Nebula, then its age must be less than 50 years. If it were the result of a supernova explosion, such a young age is unacceptable since the supernova should have been observed.

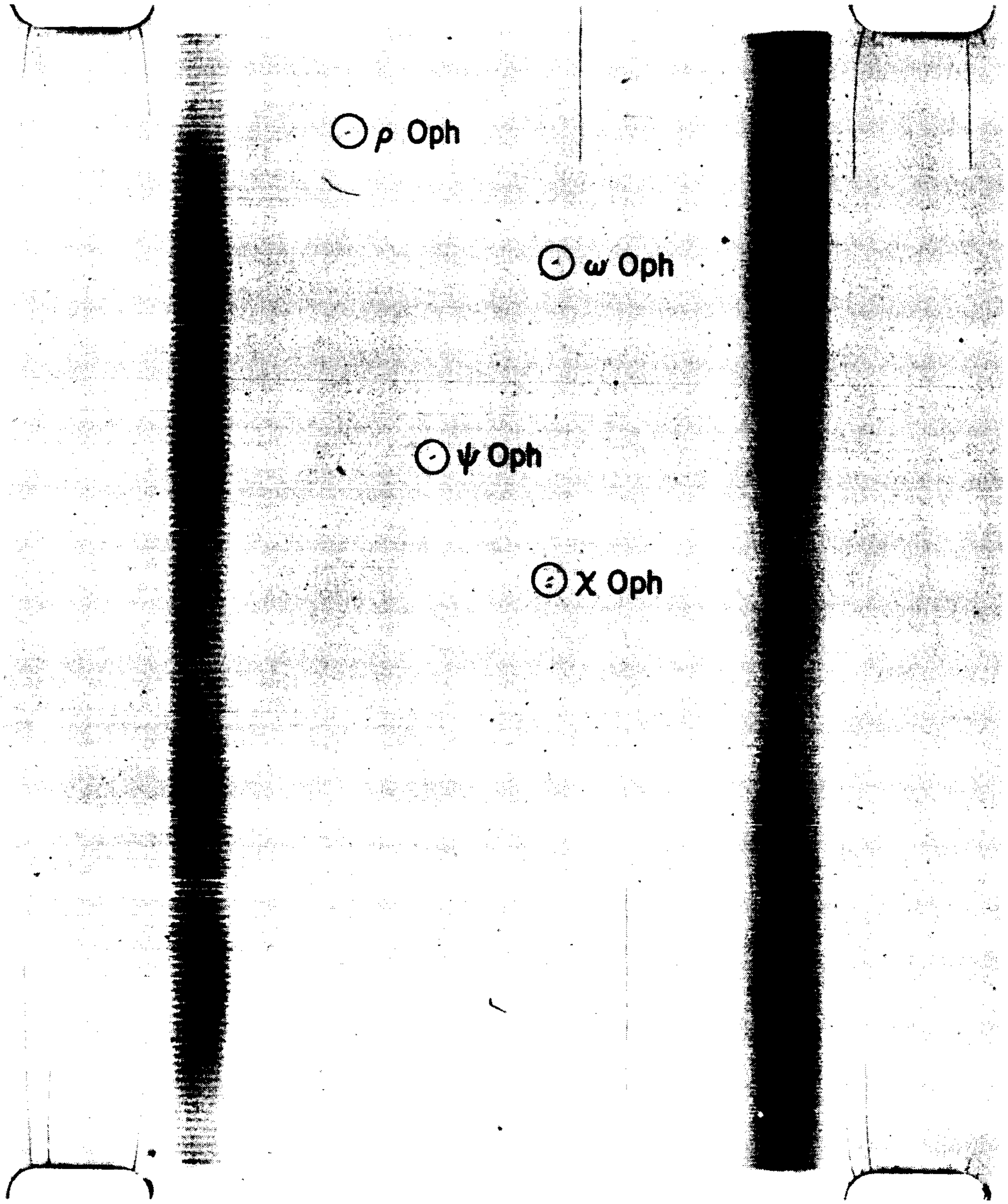

Fig. 2.—A 1-sec exposure of the star field obtained at 295 sec after launch. On the edge of the frame are the images of the fiducial light. The images of the stars are elongated due to the drift of the rocket axis during the exposure.

In the third place, we consider the lack of a prominent feature in visible light within the circle of uncertainty (0°.5) of the Sco X-1 location. Any emission process (e.g., free-free emission from a hot gas or synchrotron radiation) occurring in a medium optically thin to its own radiation produces a spectrum in which the power per unit frequency interval remains approximately constant or increases with decreasing frequency. It follows that, if Sco X-1 is an optically thin object, the radiation in the optical band of the spectrum computed on the basis of the measured flux in X-rays should be at least equivalent to that from a thirteenth-magnitude star. Diluting this radiation over a disk of 20″ would produce an object with a surface brightness of about nineteenth magnitude per square second of arc. On the basis of a count of faint nebulosities made during a detailed survey of the region including Sco X-1 in a search for an object that might be the X-ray source, Johnson (1966) estimates the effect of interstellar absorption to be about 2 mag. We have examined plates of the region surrounding Sco X-1[1] and found no evidence for a nebular object of the expected brightness. The survey made by Johnson (1966) also gave negative results.

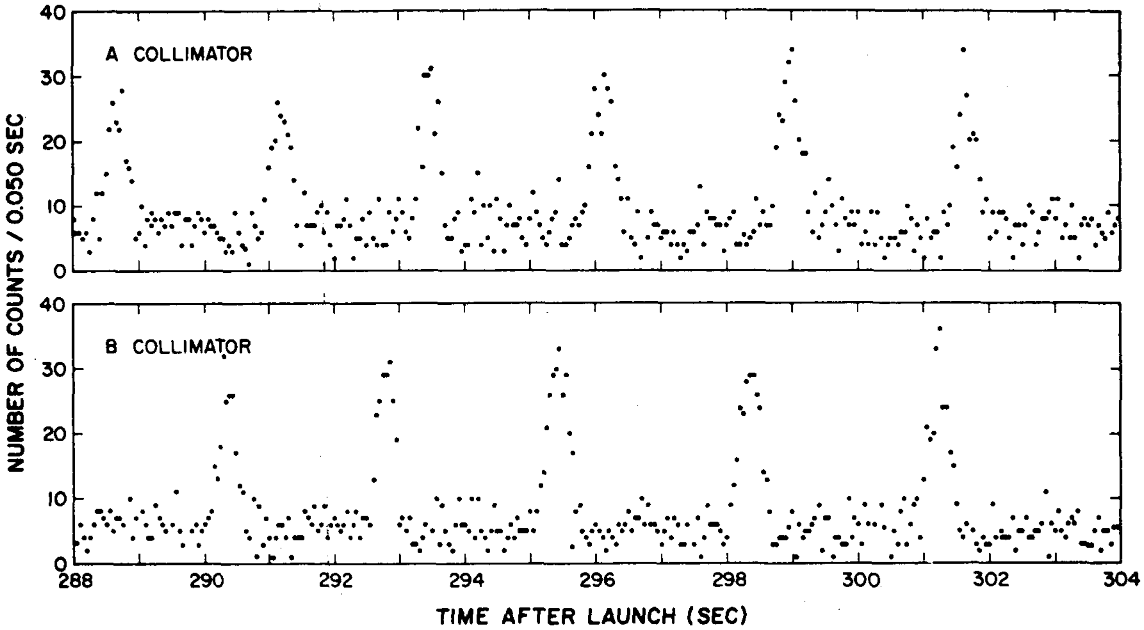

FIG. 3.—Actual counts accumulated during 0.050 sec from each collimator plotted as a function of time after launch. The two collimators differed in their band separation by 5 per cent, which causes a gradual change in phase between the two sets of peaks. The difference in the times of appearance of the peaks in the two collimators will be used to determine location.

Barring the possibility that the visible image of the X-ray source is obscured by absorption at the source, we arrive at the conclusion that the source is not a large-diameter nebulosity, but rather one of the many stellar-like objects that appears in this part of the sky. The angular diameter then shrinks to considerably less than 20″. In this case equation (1) shows that, unlike the X-ray source associated with the Crab Nebula, Sco X-1 cannot be explained on the basis of an expanding supernova remnant located anywhere in our Galaxy. Of course, the neutron-star hypothesis is compatible

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[1] Plate A20963 taken May 23–24, 1939, with the 24-inch Bruce doublet telescope at Bloemfontein, South Africa, courtesy of Harvard Observatory; plate ED2007 taken August 2–3, 1965, with the 120-inch Lick telescope, at Mount Hamilton, courtesy of M. Burbidge; plate PS-8669 (July 6–7, 1964), plate PS-8668 (July 6–7, 1964), and plate PS-8550 (May 12–13, 1964) taken with the 48-inch Schmidt telescope, Palomar, courtesy of A. R. Sandage.

with the present measurement; however, the predicted black-body spectrum is not in agreement with the available spectral observations in X-rays (Giacconi, Gursky, and Waters 1965; Chodil, Jopson, Mark, Seward, and Swift 1965).

The above considerations appear to exclude supernova remnants or, in fact, any known stellar structures as the possible origin of the observed X-ray emission. We conclude, therefore, that we have established the existence of a new class of celestial objects that are powerful X-ray emitters, which are not associated with supernovae and which, if observable, appear in visible light as starlike objects.

We are grateful to Professor Bruno Rossi, Massachusetts Institute of Technology, for many helpful discussions in connection with this experiment. We also wish to acknowledge the contribution given in the computation of astronomical coordinates by G. Ouellette. 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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APPENDIX B

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X-RAY EMISSION FROM SCO X-1

The new bound on the angular diameter of the X-ray source in Scorpio established by Gursky, Giacconi, Gorenstein, Waters, Oda, Bradt, Garmire, and Sreekantan (1966) indicates the existence of a new class of celestial objects. In this Letter we explore briefly the possibility that these objects (for convenience, referred to hereinafter as "extars") are members of the Galaxy and suggest a possible role played by them in stellar evolution.

The bound for the size of the extar, Sco X-1, viz., $\delta \ll 20''$, permits us to put an upper bound on the distance, D, to that source if the X-rays are of synchrotron origin.[1] (Here, for the sake of definiteness, we shall assume the source size to be $1''$.) The basis for this bound on distance to Sco X-1 is an argument put forth by Hoyle, Burbidge, and Sargent (1966), to disprove the estimates of cosmological distances for quasi-stellar sources. It is derived from the requirement that electron energy losses by inverse Compton effect cannot exceed losses by synchrotron emission, and the assumption that the size of the source is limited by the lifetime of the radiating electrons. Their result may be cast into the following form

$$D < 3.37 \times 10^{7} \delta^{1/2} \nu_c^{-1/2} S^{-3/4} \text{ kpc}\,, \tag{1}$$

where ν_c is the critical frequency at which the bulk of the radiation is emitted and S is the measured radiant flux in ergs cm^{-2} sec^{-1}. For Sco X-1, in addition to the new estimate of δ, the best present values of the relevant parameters are $\nu_c \sim 10^{18}$ c/s, and $S \sim 1.6 \times 10^{-7}$ erg cm^{-2} sec^{-1}. From this,

$$D < 9 \text{ kpc}\,; \tag{2}$$

i.e., on the assumption that Sco X-1 emission is largely synchrotron radiation, it follows immediately that it must be a member of the Galaxy.

It should be noted that synchrotron X-ray emission from Sco X-1 is not excluded by the recent determinations of its energy spectrum (Giacconi, Gursky, and Waters 1965; Grader, Hill, Seward, and Toor 1966). In fact, a sufficiently sharp cutoff on the high side of the relativistic electron energy spectrum will yield an exponential photon spectrum indistinguishable at present from that generated by a hot plasma. Thus consider, for

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[1] A lower bound on the distance to Sco X-1 may be obtained if it is assumed to consist of an optically thin hydrogenic plasma, at a temperature of $T \sim 5 \times 10^{7}\,^{\circ}$K (cf. Manley 1966). First we obtain a bound on the size of the source consistent with the lack of significant cooling since its discovery in 1962. It is evident that the principal cause of cooling implicit in this model is the nearly adiabatic expansion of the hot plasma. Assume that the plasma behaves like an ideal gas with an adiabatic index $\gamma = \frac{5}{3}$. It follows

$$\frac{dT}{dt} \approx \frac{-2Tv}{R}\,,$$

where v is the velocity of expansion given approximately by the thermal speed of the protons and R is the radius of the expanding sphere. For a fractional temperature change smaller than, say, ϵ per year, it is found that

$$R > 7 \times 10^{15}/\epsilon \text{ cm}\,.$$

From the estimate of the angular size of this extar

$$\delta \equiv \frac{2R}{D} \sim 5 \times 10^{-6} \text{ radians}\,,$$

we find then that

$$D > 1/\epsilon \text{ kpc}\,,$$

where D is the distance to Sco X-1. Thus, for instance, if ϵ is smaller than 5 per cent per year, R must exceed 0.04 pc and $D > 20$ kpc; i.e., the object is metagalactic.

example, the spectrum produced by a flat electron energy distribution function, $N(\gamma)$, extending to a maximum of $\gamma_m \gg 1$:

$$N(\gamma)d\gamma = \frac{N_0}{\gamma_m}d\gamma\,, \qquad 1 \leq \gamma < \gamma_m\,, \qquad (3)$$
$$= 0\,, \qquad \gamma > \gamma_m\,,$$

where $\gamma = (1 - v^2/c^2)^{-1/2}$, and N_0 is the number density of relativistic electrons. The spectral intensity function F_ν is found to be (Ginzburg 1964)

$$F_\nu \approx \frac{\sqrt{(3)}\,e^3 H N_0}{m c^2}\sqrt{x}\int_x^\infty d\eta(\sqrt{\eta} - \sqrt{x})K_{5/3}(\eta)\,\mathrm{ergs\ cm^{-3}\ sec^{-1}\,(c/s)^{-1}}\,, \qquad (4)$$

where H is the magnetic field,

$$x \equiv \nu/\nu_c\,, \qquad \nu_c \equiv \frac{3}{4\pi}\frac{eH}{mc}\gamma_m{}^2\,,$$

and $K_p(x)$ is the modified Bessel function of the second kind. In Figure 1 a plot of the function

$$f(x) = \sqrt{x}\int_x^\infty d\eta(\sqrt{\eta} - \sqrt{x})K_{5/3}(\eta) \qquad (5)$$

is shown. Note that for $x > 1$

$$f(x) \sim e^{-x}/x^{1/2}\,;$$

i.e., the spectrum is nearly exponential. Moreover, over three decades of energy immediately prior to the exponential decrease, the spectrum is nearly flat, as is the case for hot-plasma bremsstrahlung. Thus, in line with this model, the identification of a thirteenth-magnitude visible object associated with Sco X-1 is not excluded. (As is well known, the customary "power law" spectrum associated with synchrotron radiation is a consequence of the assumed electron power law distribution.) In Figure 2, we show a fit to some recently obtained spectral data from Sco X-1 (Grader *et al.* 1966). With $h\nu_c \approx$ 4.5 keV, there follows that

$$H\gamma_m{}^2 \approx 3 \times 10^{11}\,. \qquad (6)$$

Although the preceding calculation was carried out for a flat electron spectrum, the exponential energy dependence on the high end of the photon spectrum will persist for more general electron spectra, provided there is a well-defined high-energy electron cutoff. Thus, when the above considerations are applied to the spectrum of the Crab Nebula (R. C. Haymes and W. L. Craddock, unpublished; see Fig. 3) there follows that $h\nu_c \approx$ 12.5 keV and hence

$$H\gamma_m{}^2 \approx 8 \times 10^{11}\,.$$

For the estimated magnetic field of the Crab, $H \sim 3 \times 10^{-4}$ gauss, this means a cutoff at $\gamma_m \sim 5 \times 10^7$; this is, of course, consistent with the estimates of electron energies necessary to produce X-rays in the 1–10-keV region.

Returning now to the discussion of Sco X-1, note that while the shape of the spectrum obtained by Giacconi *et al.* (1965) is very similar to that obtained by the LRL group (Grader *et al.* 1966), the latter's counting rate is three times higher than that obtained for the same source by other investigators. This discrepancy and its significance have not as yet been resolved. With this cautionary remark in mind, we shall now deduce some physical properties implied by this model of Sco X-1. After integration of expression (4) over all frequencies, it is found that the surface intensity, I, is related to the measured quantities δ and S as follows:

$$I \equiv \frac{R\sqrt{(3)}\,e^3 H N_0 \nu_c}{m c^2} \sim \frac{12 S}{\delta^2}\,\mathrm{ergs\ sec^{-1}\ cm^{-2}}\,. \qquad (7)$$

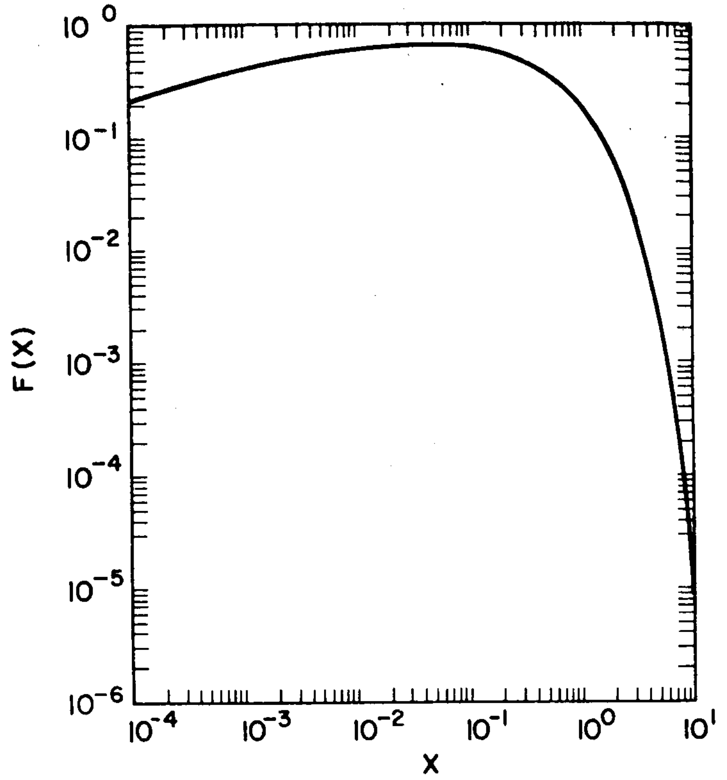

Fig. 1.—Normalized synchrotron spectrum for a flat electron energy distribution

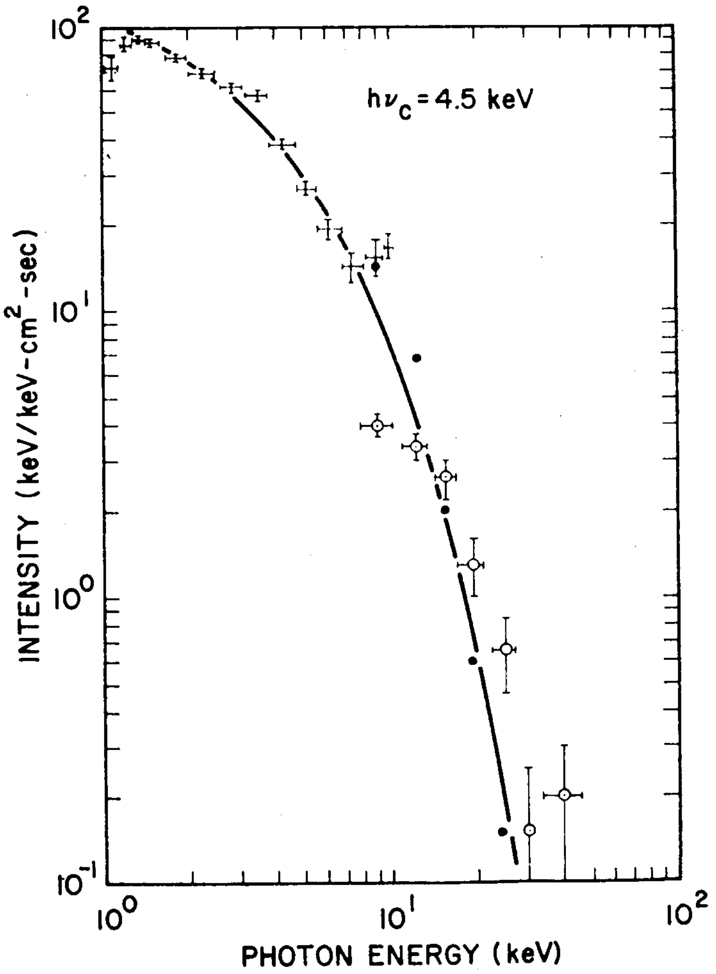

Fig. 2.—Synchrotron spectrum fit to X-ray spectrum from Sco X-1; measured by Grader *et al.* (1966).

Inequality (2) yields a bound on the size R of the source:

$$R < 2.5 \times 10^{-2}\ \mathrm{pc}\,. \tag{8}$$

From this it is found, on using equation (7), that

$$HN_0 > 2\sqrt{3} \times 10^{-9}\,. \tag{9}$$

To proceed further, assume as a working hypothesis the minimum energy principle of Ginzburg (1964). According to it, when synchrotron emission prevails, the sum of the energy in the magnetic field and in the relativistic electrons is at a minimum. For a given synchrotron power output, this occurs when the magnetic field density is approximately equal to the relativistic electron energy density,

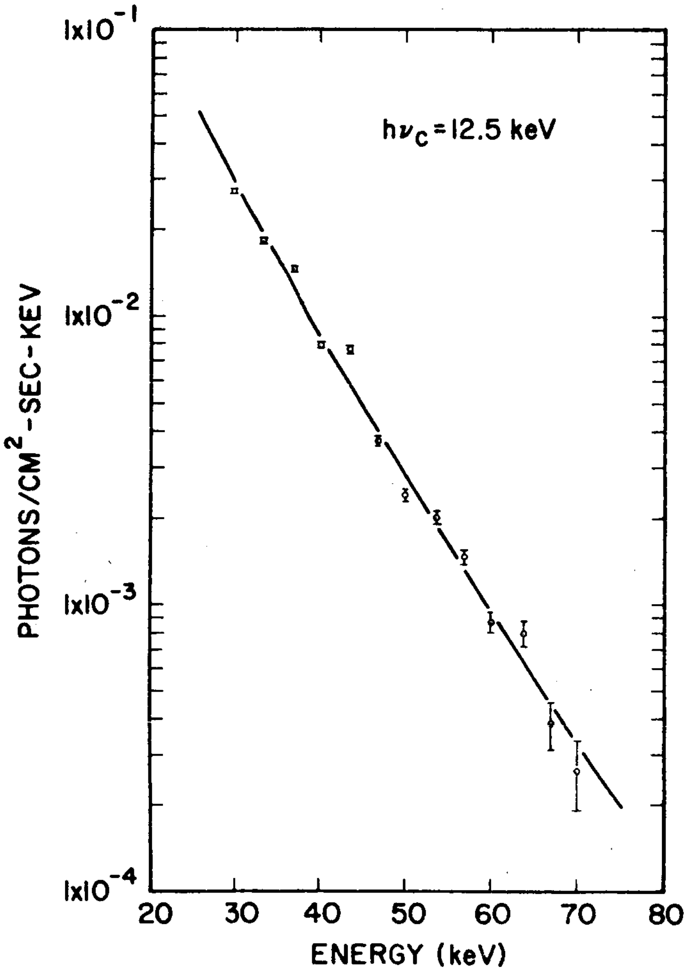

FIG. 3.—Synchrotron spectrum fit to high-energy X-ray emission from Crab Nebula; measured by R. C. Haymes and W. L. Craddock (preprint).

$$N_0\gamma_m \sim \frac{H^2}{8\pi m_0 c^2}\,. \tag{10}$$

On combining equations (6), (9), and (10) it is found that

$$H > 7.5 \times 10^{-3}\ \mathrm{gauss}\,, \qquad \gamma_m < 6 \times 10^6\,, \qquad N_0\gamma_m > 3\ \mathrm{cm}^{-3}\,. \qquad (11$$

These results imply that the energy density within the source is in excess of 1.5 MeV cm^{-3} and considerably more than is found in a supernova remnant like the Crab Nebula. There arises then immediately the question of the significance of this object.

We propose here that Sco X-1 is a protostar shedding its magnetic field. As is well known, a major stumbling block in all theories of stellar evolution is the lack of a rapid dissipation mechanism for the primordial magnetic field trapped in the protostellar material (Burbidge and Burbidge 1958). Briefly, we suggest that at a critical point in the evolution in a protostar the magnetic field energy is used up by producing high-energy electrons which, upon interaction with the selfsame magnetic field, radiate away their energy. This process presumably continues until the magnetic field is largely dissipated, or until the density of the protostellar material increases to the point where collision losses exceed synchrotron emission losses. Note that this mechanism does not require any significant input of energy from the protostellar material, except for the gravitational energy used in compressing the magnetic field.

That extars are in fact protostars is suggested by the following. First, the magnetic field estimated in formulae (11) is about the magnitude that an interstellar field would increase to by the time the material in 1 pc^3 will have shrunk to the dimensions given by expression (8). Second, if it is assumed that the present stellar population of the Galaxy is in an approximate steady state, then the rate of occurrence of white dwarfs must be offset by creation of new stars. Now the rate at which stars turn into white dwarfs is estimated at $\sim 10^{-12}$ pc^{-3} $year^{-1}$ (Schatzman 1958). On the other hand, the magnetic energy contents of an extar like Sco X-1 based on the estimates in formulae (11) suffices for it to last for 30 years or more. Then the steady-state number of extars in the Galaxy is about twenty, which is to be compared with about a dozen X-ray sources noted thus far and not identified with supernovae.

The immediate observable consequences of our model are as follows: (*a*) as the protostars evolve they cease to emit X-rays and eventually appear in the visible as young stars; and (*b*) new extars will appear from time to time as new stars begin to form.

The author wishes to acknowledge fruitful discussions with B. B. Rossi and W. A. Fowler at Massachusetts Institute of Technology and J. W. Carpenter at American Science and Engineering, Inc. The help of Y. M. Treve, of American Science and Engineering, Inc., in calculating the synchrotron spectrum is also gratefully acknowledged. This work has been sponsored in part by contract NASw-1284. ✓

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APPENDIX C

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

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We have measured the location of ScoX-1, the strong X-ray source in Scorpio, with a precision of about 1 arc minute. ScoX-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 (1964a) 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 Fig. 1 and listed in Table II.

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 8 March 1966. The recent report by Gursky, Giacconi, Gorenstein, Waters, Oda, Bradt, Garmire and Sreekantan (1966) that the angular size of ScoX-1 is less than 20 arc seconds 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 I.

Individual pulses from the X-ray counters were stretched to 0.5 milliseconds 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.

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 second 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, ScoX-1 was observed for about 55 seconds. The X-ray data taken during that portion of the flight is 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 to 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 4.5°/sec around the central axis of the collimator. At about the same time aerodynamic effects (the rocket was beginning to reenter 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' 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% in the angular separation of their transmission bands. Twenty bands from the "short" collimator are separated by about the same total angle as 21 bands from the "long" collimator. Thus, the two collimators provide a vernier scale, which is repeated every 1° 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° 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 collimators 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 rotation of the sensitive axis occurs, successive transists 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 II.
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 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 results of these errors in 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 R. A. and ± 7" in δ. 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 I 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%. The maximum error in position that could arise from this uncertainty is about 30". Accordingly, we assigned an uncertainty of $\pm 4^s$ in R. A. and ± 30" in δ to our measurement as our best estimate of positional uncertainty.

As an overall 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, 1964b), also detected in this experiment, and the known position of the nebula. While the data was of much lower statistical precision than that obtained for ScoX-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 ScoX-1 here reported is at least 30 arc minutes 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 (1964a) 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 Fig. 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 ScoX-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.

ACKNOWLEDGMENTS

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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TABLE I
Instrumentation Specifications

Modulation Collimators

	Long Collimator	Short Collimator
Band Width	72"	76"
Separation between Bands	5' 1.91"	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%)

TABLE II

α (1950.0)	δ (1950.0)
$16^{hr}\ 17^{m}\ 7^{s} \pm 4^{s}$,	$-15^{o}\ 30'\ 54'' \pm 30''$
$16^{hr}\ 17^{m}\ 19^{s} \pm 4^{s}$,	$-15^{o}\ 35'\ 20'' \pm 30''$

Best positions of ScoX-1 determined in this experiment. The two positions are about equally probable; additional positions shown in Fig. 1 are substantially less probable.

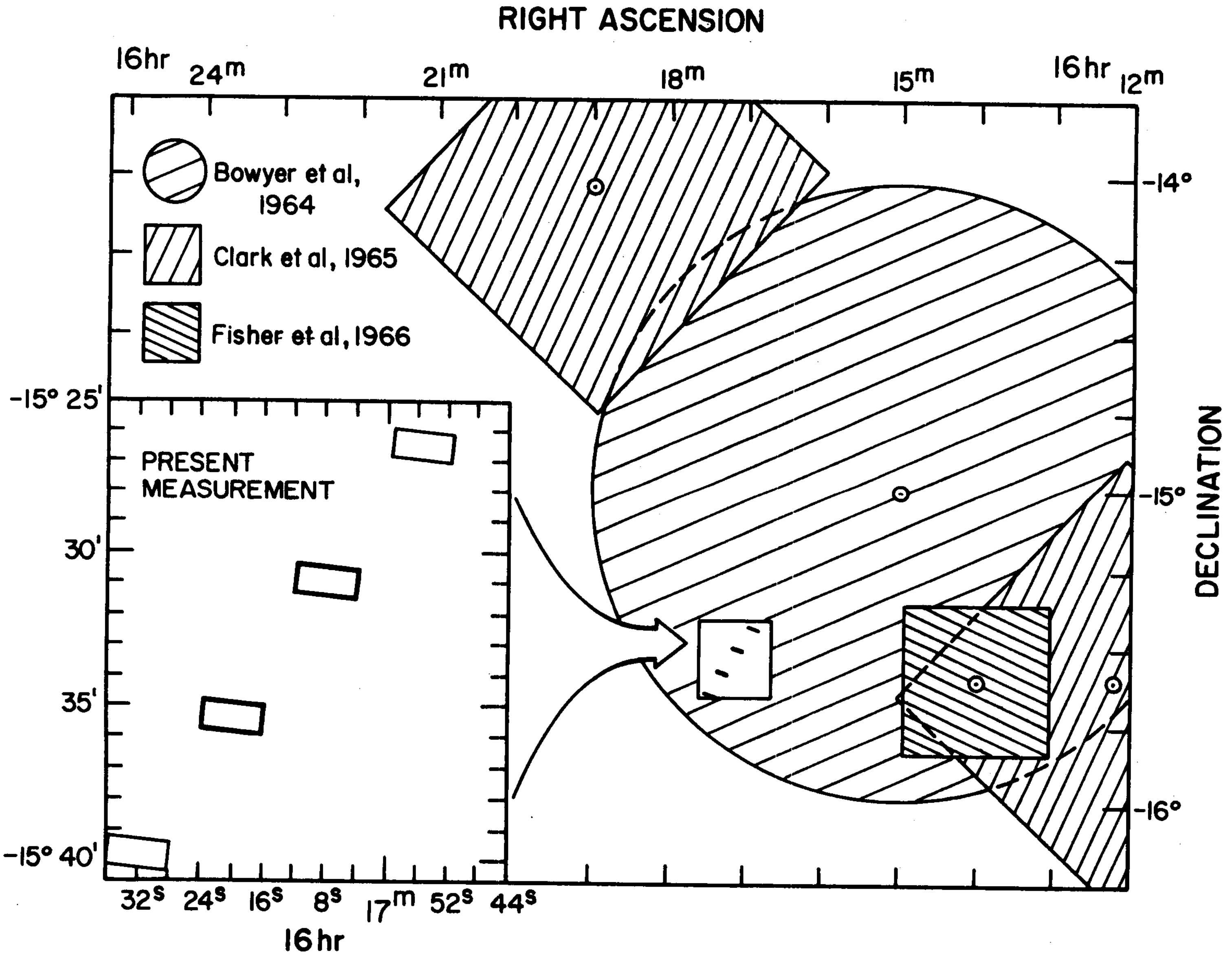

Fig. 1 The location of ScoX-1. The results of the present experiment are shown with results from previous experiments.

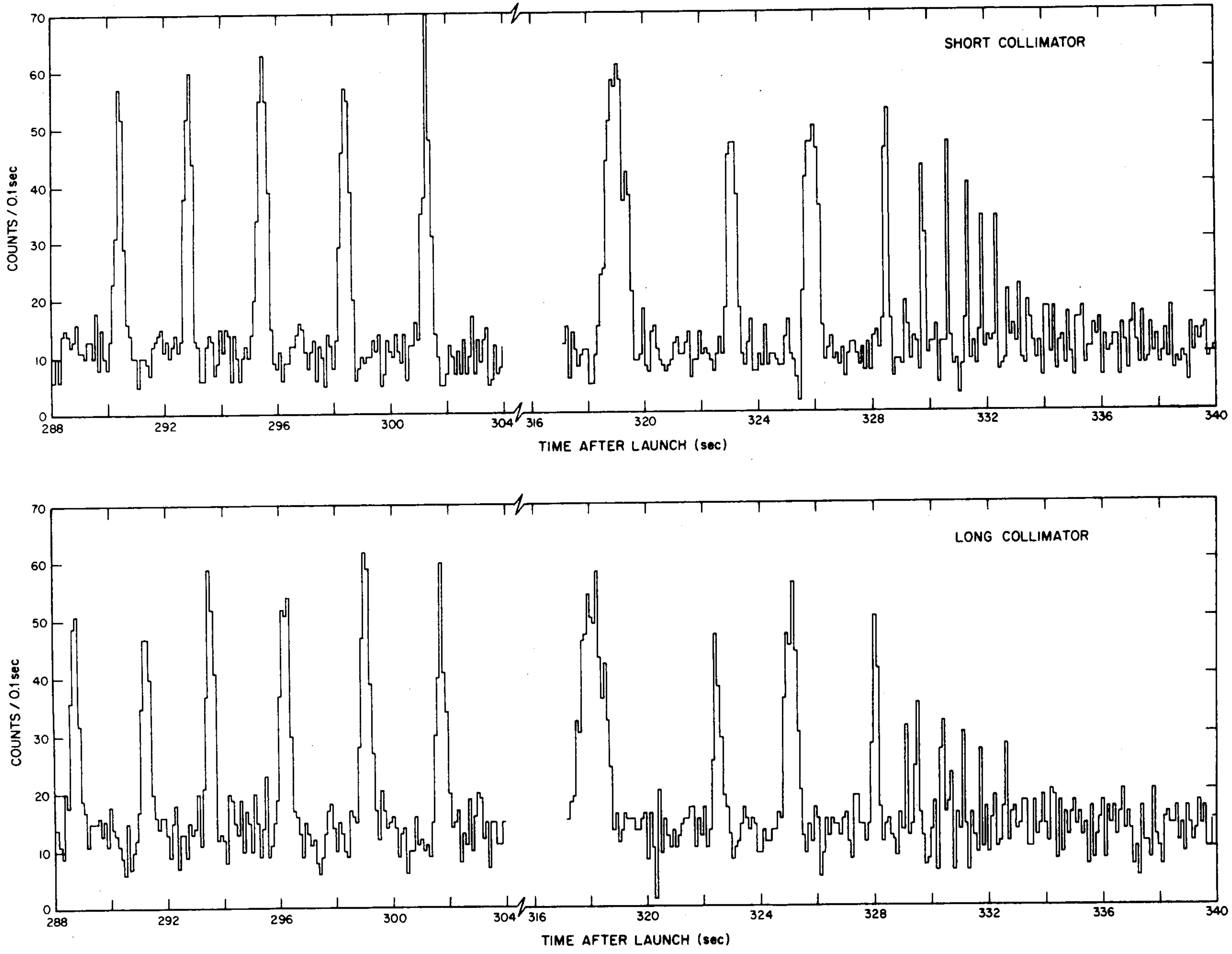

Fig. 2 Histogram of actual counts in the energy range from 1 to 24 kev and accumulated per 0.1 seconds during the time that ScoX-1 was within the field of view of the collimators.

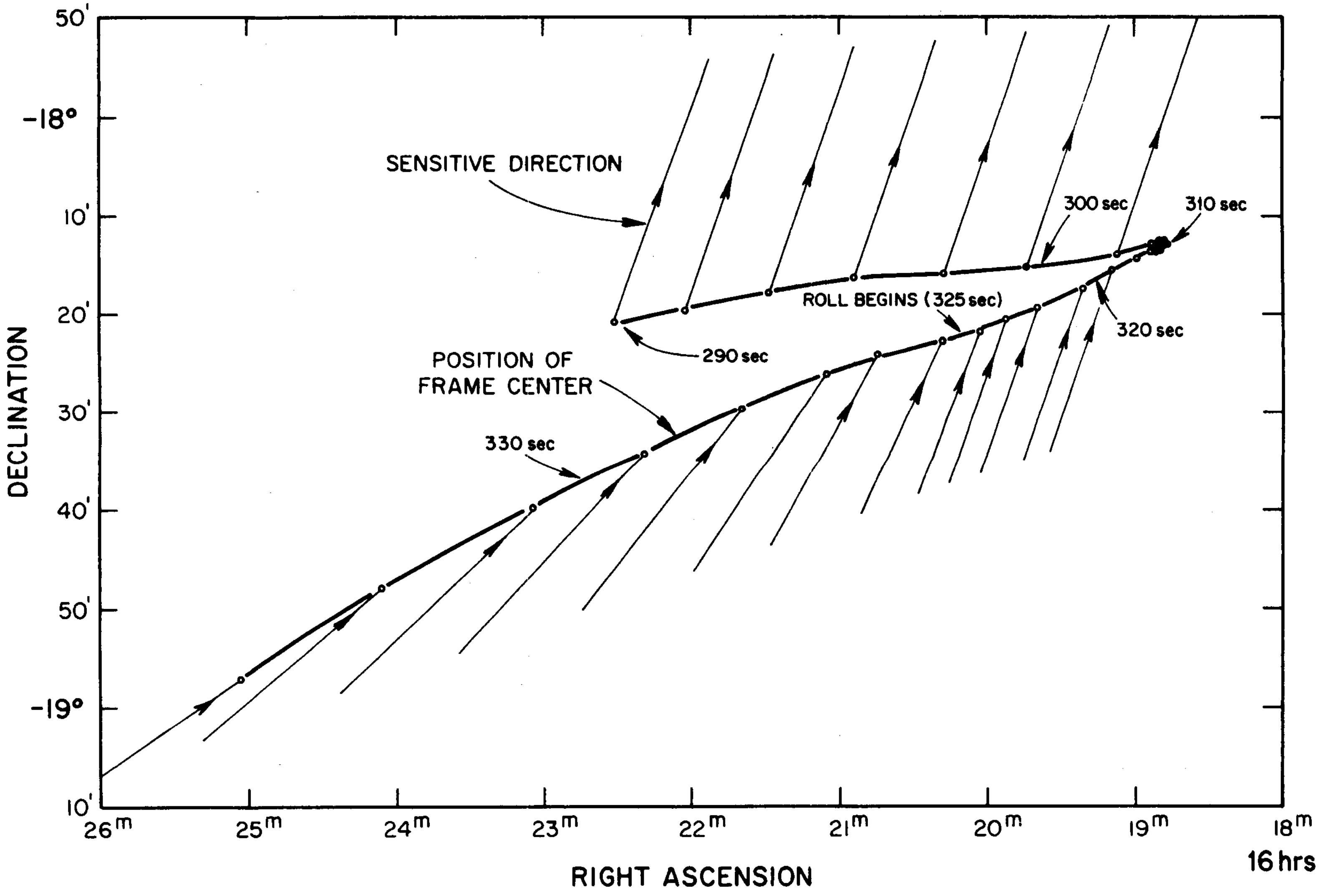

Fig. 3 Motion of the frame center and orientation of the sensitive direction during the observation of ScoX-1. The frame center, which is defined as the geometric center of the aspect photographs, was approximately aligned with the central axes of the modulation collimators. Dots indicate 2 sec intervals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

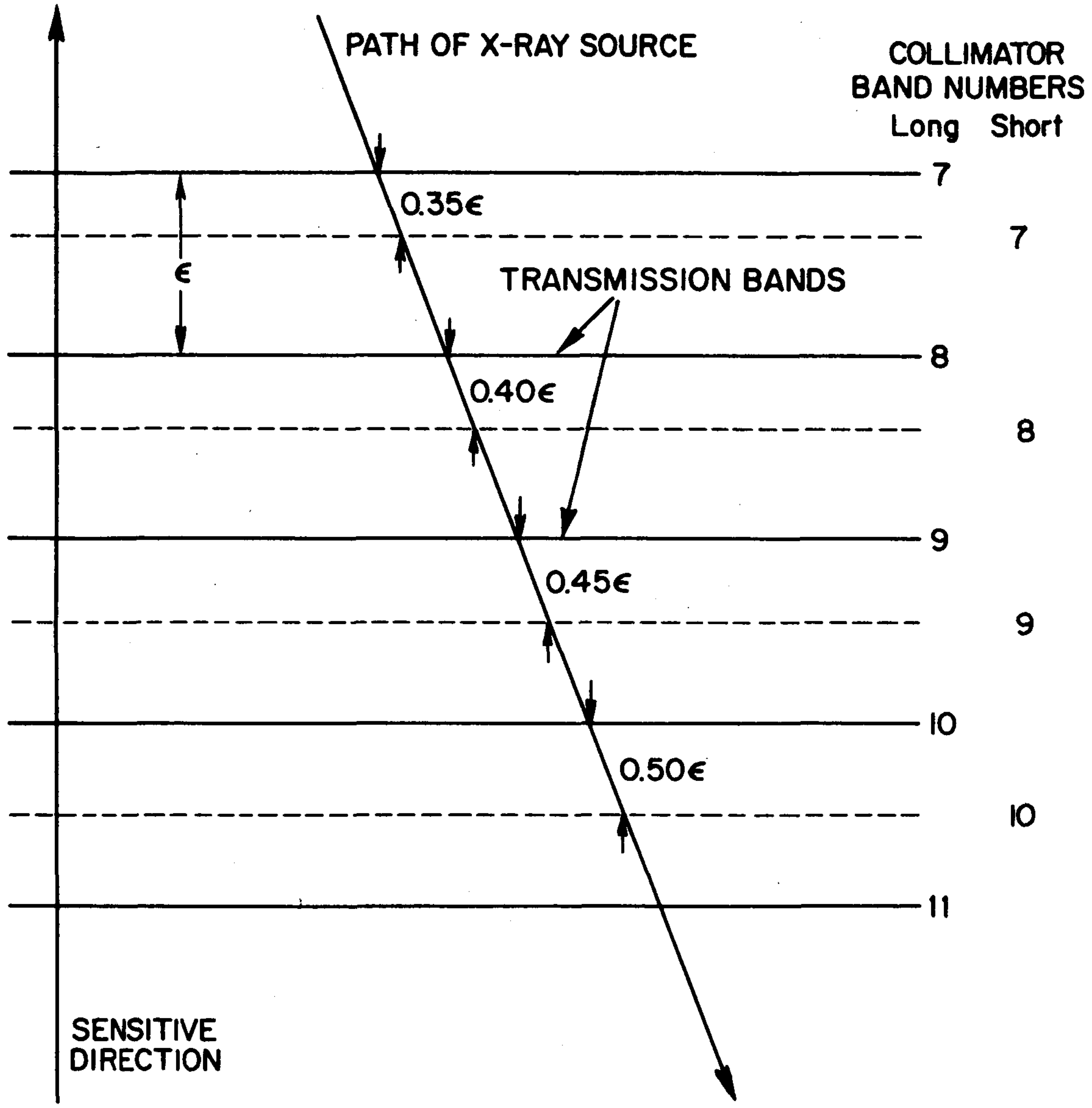

Fig. 4 Schematic representation of several of the X-ray transmission bands from the two collimators as they appear on the aspect photographs. As successive pairs of bands are traversed, the angular separation of source transits, across correspondingly numbered bands, increases by about 0.05ϵ.

APPENDIX D

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ON THE OPTICAL IDENTIFICATION OF SCOX-1

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An optical search has been made of the sky surrounding the new position of ScoX-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 star-like, (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, Giacconi, Gorenstein, Waters, Oda, Bradt, Garmire and Sreekantan (1966B) on the measurement of an upper limit of 20" to the diameter of ScoX-1. The predicted lower limit on the visible magnitude was obtained by extrapolating the energy distribution from the observed range of 1A to 10A 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 103a0 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 ($\bar{\lambda} \simeq 3600A$) and a Hoya L-39 filter ($\bar{\lambda} \simeq 4400A$). 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 minute 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 ± 0.2 (m.e.), B-V = + 0.3 ± 0.05 (m.e.), and U-B = -0.8 ± 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 90A/mm at 4000A and 150A/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 λ 4686.

These results were communicated by cable to Giacconi, who relayed them by telephone to Palomar on June 23, PST. 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 one minute 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 minutes 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% (0.02 mag.) in several minutes. In one interval the U magnitude changed by 0.09 mag. in 8 minutes.

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 $H\beta$, HeII (λ 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 $\alpha(1950) = 16^h\ 17^m\ 4.3^s$, $\delta(1950) = -15^\circ\ 31'\ 13''$. 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 sec of arc 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 minutes, 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 ± 1/2 degree of the new X-ray position.

Also identified in Figure 1 are several stars whose U, B, V 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 to 8 mag. (100 to 400 parsecs). Thus interstellar absorption and reddening do not adversely affect the observation of ScoX-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 $\overline{V} = 12.95$ with a range of $\Delta V = 0.08$ mag. in the 12 minute observation interval. The colors remained relatively stable at $B-V = +0.20$, $U-B = -0.76$. These values are appreciably different from $\overline{V} = 12.39$, $B-V = +0.23$, and $U-B = -0.88$ measured two and a half weeks earlier on June 24 UT. Continued observations on 7 successive nights with the 20 inch telescope, primarily in the B wavelength band (λ 3800A to λ 5400A), are shown in Figure 2. Spectra were obtained during the times indicated by the horizontal bars on July 13 through July 18.

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

The spectra taken in the July 13 - 18 interval were obtained with the 200 inch Hale reflector at a linear dispersion of 85A/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 $\overline{V} \simeq 12.6$ to $\overline{V} \simeq 13.4$ and back again to $\overline{V} \simeq 12.6$. The blank spaces in the individual spectra are time marks made by closing the dark slide of the camera for 2 minutes 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 due probably to C III, N III, and possible 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. 7A, 6. 2A, and 2. 1A on the respective three nights while He II(4686) had E. W. 's of 3. 6, 2. 9 and 2. 8A.

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. + HeI + HeII line at λ 3836A. There are also indications from partially completed measurements that the wavelengths of other emission lines, notably HeII (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 ScoX-1 [assuming that the identification is correct and that $\bar{B}_o = 12.1$ 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 parsecs. This interval might be narrowed down by considering that the optical spectrum of ScoX-1 resembles somewhat that of DQ Her, CP Pup, and V603 Aql where $\overline{M}_B \simeq 5.3$ (Payne-Gaposchkin 1957, Chapter 1) giving a distance of about 250 parsecs. The latitude of $b^{II} = +24^o$ gives a height above the plane of about 100 parsecs which is quite characteristic of novae (Payne-Gaposchkin 1957, Table 2.4). It should be emphasized that this quoted value of the distance is strictly a consequence of the assumption that ScoX-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 ScoX-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 to 10A 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 to 10A 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 disc-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 $T \simeq 5 \times 10^7 {}^\circ K$, 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 et al, 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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TABLE 1

Photometry of Stars in the Field of ScoX-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	0.27	0.23	6.7	
1	14.97	0.94	0.41	0.28	8.4	
2	16.25	1.05	0.43	0.46	9.2	
3	14.17	1.16	0.87	0.21	6.7	
4	14.47	0.84	0.33	0.18	8.4	
5	14.46	0.83	0.26	0.27	8.6	
ScoX-1	12.43	0.23	-0.86			June 24 U.T., 1966 Selected data over a time interval of 43 minutes
	12.44	0.23	-0.84			
	12.39	0.22	-0.92			
	12.38	0.24	-0.89			
	12.38	0.24	-0.91			
	12.43	0.22	-0.88			
	13.01	0.21	-0.76			July 12 U.T., 1966 Data over a time interval of 12 minutes
	12.97	0.20	-0.73			
	12.94	0.20	-0.74			
	12.95	0.19	-0.76			
	12.94	0.21	-0.76			
	12.93	0.21	-0.76			

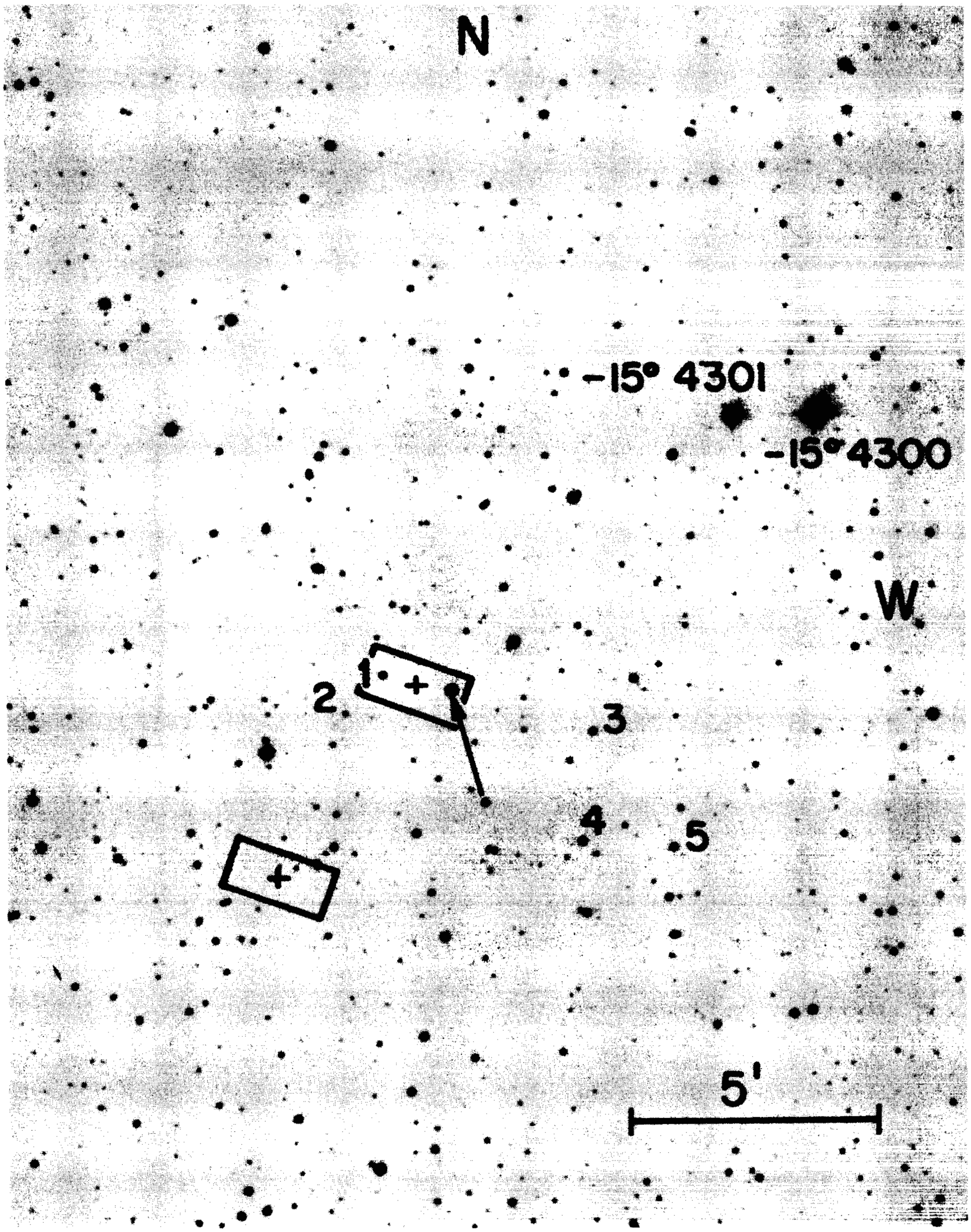

Fig. 1 Photograph of the region containing the new X-ray position of ScoX-1, reproduced from the Palomar Sky Survey prints. The two equally probable X-ray positions are marked by crosses surrounded by a rectangle of 1 by 2 arc minutes. The object described in the text is marked with an arrow. The identifications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

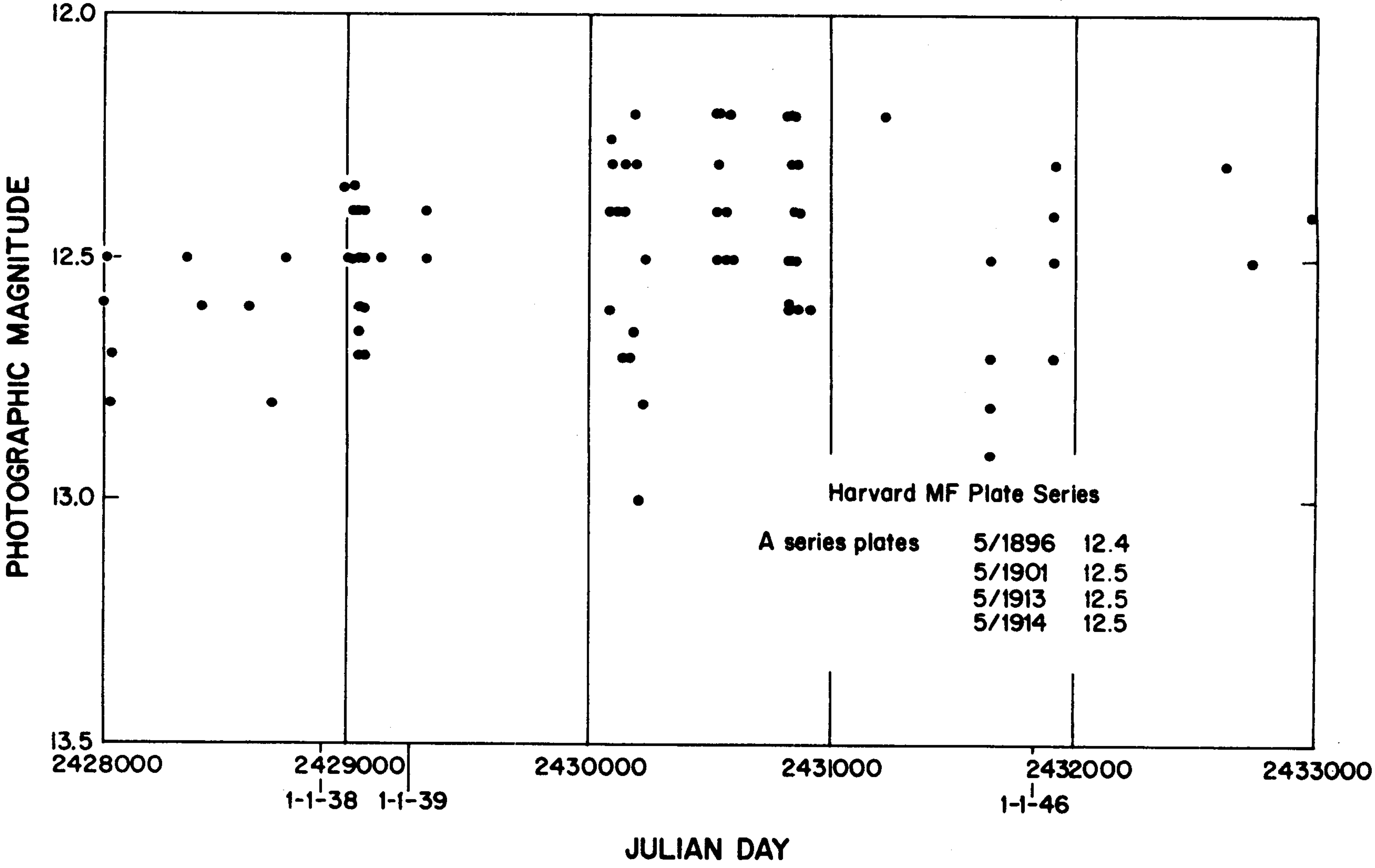

Fig. 3 Estimates of the magnitude of the candidate object from old plates in the Harvard collection. The zero point and the scale of the photometric system is only approximate.

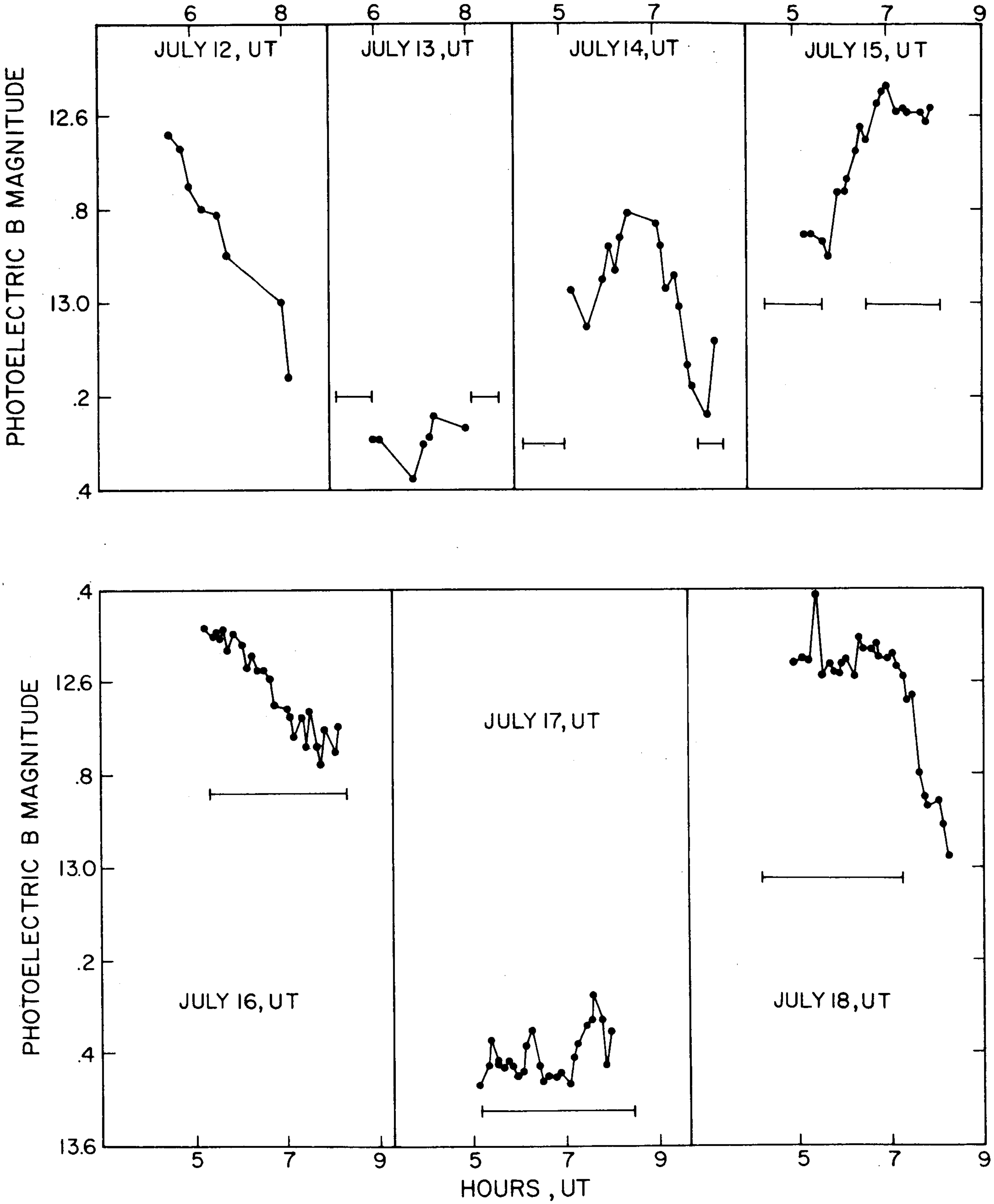

Fig. 2 Photoelectric B magnitudes of the candidate object as obtained with the Palomar 20 inch reflector. Horizontal bars indicate the times when spectrograms were obtained with the 200 inch Hale telescope.

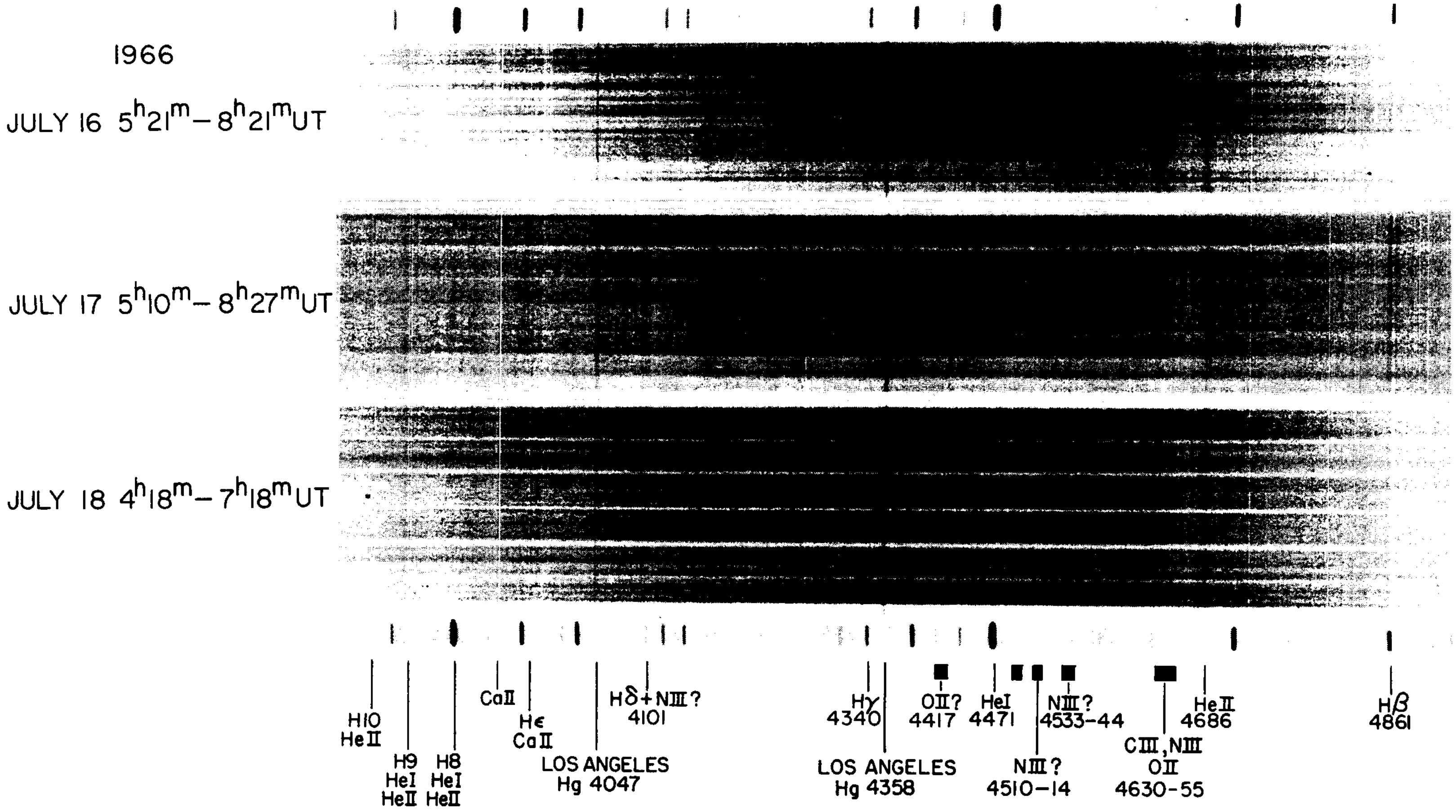

Fig. 4 Three continuously trailed spectra in the blue spectral region. Time marks, made by closing the camera dark slide, are evident on the last two. Tentative line identifications are indicated. The comparison arc is He. The original dispersion was 85A/mm.

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