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Some Recent Results of X-ray Astronomy*

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X-ray astronomy is now little more than four years old. The progress made by this branch of science in this comparatively short period has been quite impressive. Some twenty localized sources are presently known. On some of them highly significant spectral measurements have been carried out, even though the resolution achieved so far has not been sufficient to detect possible emission lines over the continuous background. One of the sources has been positively identified with the Crab Nebula, by the remarkable lunar occultation experiment carried out by Friedman's group in the summer of 1964. Another source might be coincident with another supernova remnant (Cas A) and two additional sources may be coincident with two extragalactic objects (M 87 and Cyg A).

Until recently, however, none of the remaining X-ray sources had been even tentatively identified with visible or radio objects. This lack of identification was particularly puzzling in the case of Sco X-1, the strong X-ray source, whose discovery in 1962 marked the beginning of X-ray astronomy.

Through the observations of three different groups, the location of this source was known with an uncertainty which, according to the more optimistic estimates was only 1/4 of a square degree while, according to the more conservative estimates, was about one square degree. The brightest star within the larger area of uncertainty had magnitude 9. And yet, at wavelengths smaller than 10 A, Sco X-1 shone with an intensity only 10 times smaller than the quiet sun. Obviously an object of such a great brightness in the X-ray region, and so unconspicuous in the visible, was nothing even remotely resembling an ordinary star.

At first it was suggested that Sco X-1 might be one of the hypothetical neutron stars that were fashionable some two or three years ago. Subsequent measurements, however, showed that the X-ray spectrum of Sco X-1 did not resemble at all the Planck spectrum characteristic of a hot, optically thick object. In fact the spectrum measured by a number of observers could be best fitted to an exponential law, such as expected if the source was a hot, optically thin cloud of fully ionized gas, radiating via bremsstrahlung. From the logarithmic slope of the spectrum, the temperature of the cloud was estimated to be of the order of 50 million ^{o}K.

To be sure, this was not the only possible interpretation of the observed spectrum. For example, synchrotron radiation by electrons with a suitably chosen energy distribution could also account for it. However, the source did appear to be transparent to its own radiation and it was thus reasonable to expect that the spectrum, i.e., the emitted power per unit frequency, should keep on increasing with decreasing frequency, or at least should tend to an approximately constant value. It was then possible from the observed X-ray flux, to estimate a lower limit for the visible brightness of Sco X-1. Disregarding interstellar absorption (which, as we shall see, is actually quite small in the direction of Sco X-1) this minimum brightness was found to be equivalent to that of a 13th magnitude star.

At this point, a second possible interpretation was offered for the absence of a conspicuous visible counterpart of Sco X-1. It was suggested that perhaps Sco X-1 might be the remnant of an ancient and relatively nearby supernova, whose core had expanded to an angular size of several arc minutes; the point being that a cloud of this size, with a total light flux equal to that of a 13th magnitude star, would have a surface brightness below the limit of detectability. The best angular resolution achieved as of the end of last year had placed an upper limit of 7 arc minutes to the angular diameter of Sco X-1. This upper limit was not yet sufficient to rule out the old supernova hypothesis that I have just mentioned.

Clearly it was of great importance to improve by a substantial amount the accuracy in the determination of both the angular size and the angular coordinates of Sco X-1. This dual aim was achieved by means of a rocket flight that took place in March of this year. While the prime mover of this experiment was Riccardo Giacconi, a number of scientists, belonging to four different organizations made important contributions. They are:

R. Giacconi, P. Gorenstein, H. Gursky and J. Waters of American Science and Engineering, Inc.

M. Oda, H. Bradt, G. Garmire and B. V. Sreekantan of the Massachusetts Institute of Technology.

A. R. Sandage and P. Osmer of the Mount Wilson and Palomar Observatories.

M. Oda, K. Osawa and J. Jugaku of the Institute of Space and Aeronautical Science and the Tokyo Astronomical Observatory.

The vehicle used was an attitude-controlled rocket. The instrumentation of this rocket represents a qualitative advance over previous techniques of X-ray astronomy. The improvement regards both the angular resolution of the X-ray detector, and the accuracy in the determination of its instantaneous orientation with respect to the stars.

The angular resolution was achieved by means of a modified version of the modulation collimator originally developed by Oda, which combines a wide field of view with a fine resolving power. The rocket contained two separate collimators of this type (see Figs. 1, 2). Each collimator was made of a series of parallel grids; its angular response consisted of a series of transmission bands, about 40" wide at half maximum, separated by a distance of about 5' (Fig. 3). The radiation was detected by beryllium-window proportional counters sensitive in the spectral region from about 2 to about 20 keV, placed behind the collimators.

The axes of both collimators were parallel to the longitudinal axis of the rocket. The attitude control system caused this axis to point in the general direction of Sco X-1, and then allowed it to drift slowly. Since the collimators have a fine angular resolution only in the direction perpendicular to the wires, the rocket was programmed to roll about its longitudinal axis at some time during the flight, so as to provide angular information in different directions.

The accurate determination of the instantaneous orientation of the collimators' axes was achieved by the inclusion in the payload of a photographic camera which, during the flight, took pictures of the sky at one-second intervals. To eliminate the possibility of systematic errors that may result from a slight change at take-off in the orientation of the optical axis of the camera relative to the axes of the X-ray collimators, a diffuse light source was arranged in such a way that the star field and the transmission bands of the collimators appeared in the same frame (Fig. 4). In this manner it was possible to determine the precise position of the transmission bands at the times when maxima of the transmitted X-ray intensity were observed.

There remained an uncertainty as to which of the transmission bands actually contained the X-ray source. This uncertainty was greatly reduced by the use of a "vernier" method, suggested by Gursky, and based on a 5 percent difference in the separation between the transmission bands of the two collimators.

Not much elaboration of the data was needed to obtain the desired information concerning the angular size of Sco X-1. When the counting rates were plotted against time, they showed a series of narrow peaks, due to the drift of the X-ray source across the transmission bands of the collimators. An example of such records is shown in Figure 5. In Fig. 6 the data corresponding to several peaks are superposed to improve the statistical accuracy, and the resulting experimental variation of the counting rate is compared with that computed for a point source. The agreement is as good as one might expect considering the unavoidable small imperfections of the collimator and the uncertainties in the superposition of the different peaks.

On the basis of this result, the authors announced last April that the angular dimensions of Sco X-1 cannot exceed 20".(1) This new upper limit - 20 times smaller in linear dimensions, 400 times smaller in area than the previous upper limit for the size of Sco X-1 - brought to a sharper focus the difficulty of explaining the absence of any conspicuous visible object in the general direction of the strong X-ray source.

As I mentioned before, the luminosity of the source was expected to be equivalent at least to that of a 13th magnitude star. Now a 13th magnitude object of 20" diameter or less is well above the visibility limit. And yet no nebulosity of the expected brightness could be found in the region of

Sco X-1. It was thus concluded that, in all likelihood, the visible counterpart of this X-ray source was a star-like object.

In the direction of Sco X-1 there are about 100 stars of 13th magnitude or brighter per square degree. Thus, for a positive identification of Sco X-1 with a visible object, it was essential to determine its position within a small fraction of one square degree. The rocket flight that I have described provided the data needed for this determination. However, the task of extracting from the data the exact position of Sco X-1 was much more difficult and time consuming than the task of determining its angular size. The analysis has now been completed.(2) It yields two, a priori equally probable locations for Sco X-1, defined by the following coordinates:

Right Ascension	Declination
$16^{hr}\ 17^{m}\ 7^{s} \pm 4^{s}$	$-15^{\circ}\ 30'\ 54'' \pm 30''$
$16^{hr}\ 17^{m}\ 19^{s} \pm 4^{s}$	$-15^{\circ}\ 35'\ 20'' \pm 30''$

The areas of uncertainty corresponding to the two locations are shown by the two rectangles at the center of the inset in Fig. 7. This figure also shows two additional rectangles, representing possible, but a priori much less likely locations for the source. The combined area of the two preferred rectangles is only four square arc minutes, or about 1/1000 of one square degree. The new locations are 0.5° or more from those reported earlier.

Preliminary results on the location of the Sco X-1 (which turned out to be very close to the final results that I have quoted) were made available last June to Oda (who had initially participated in the experiment as the senior member of the M.I.T. group, but had by that time returned to Japan), and, through him, to the staff of the Tokyo Observatory; as well as to A. R. Sandage and his colleagues at the Mt. Wilson and Palomar Observatories.

With this new knowledge of the position, a search was undertaken for the visible counterpart of Sco X-1. To repeat what I said, this was expected to be a star-like object of about 13th magnitude. Moreover, it should have had an essentially flat spectrum in the visible and ultraviolet regions, and therefore, should have appeared much more "blue" than ordinary stars.

A two-color image plate (one in the blue, one in the ultraviolet) was taken at the Tokyo Observatory on June 17/18. It revealed the existence of an intense ultraviolet object of visible magnitude 13 near the center of the search area.(3) Photoelectric photometry confirmed this result and showed that the spectrum is essentially flat in the visible, so that the object appears much more "blue" than ordinary stars. A spectrogram taken on June 18/19 gave a continuum spectrum, with no absorption features, but with faint emission lines.

On June 23, photoelectric observations with the 200-inch Palomar reflector confirmed these results. Moreover they showed that the visible light flux from the object varies irregularly by a few percent in several minutes.

A second and improved spectrogram taken at the Tokyo Observatory on June 25/26 clearly showed the emission lines of H and He against a "blue" continuum.

The position of the object was measured at both the Tokyo and the Palomar Observatories. The result was:

right ascension:	$16^{hr}\ 17^{m}\ 4.3^{s}$
declination:	$-15^{\circ}\ 31'\ 13''$

A photograph of the sky showing the object in question (arrow) and the two most likely positions for the X-ray source (each surrounded by a rectangle of 2 by 1 minutes, corresponding to the observational uncertainty) appears in Fig. 8. The object is about 30" away from one of the most likely positions.

Thus an object of the predicted magnitude and with the predicted color characteristics was indeed found within the very small area of uncertainty for the position of the X-ray source. It was natural to conclude, as the authors did, that this object is the visible counterpart of Sco X-1.

I feel that the chances of a mistaken identification are exceedingly slim. In the first place, while the a priori probability of finding a star of 13th magnitude or brighter within an area of 4 square minutes is 1/10, the probability of finding a "blue" object of this magnitude within the same area is many orders of magnitude smaller. In the second place, no other candidate is available. The next brightest object within the area of uncertainty has magnitude 15, and has the appearance of a normal star. Moreover, a search for "blue" objects conducted at the Tokyo Observatory failed to detect any within a circle of 1/2 degree radius around the position of Sco X-1.

In order to determine whether the visible counterpart of Sco X-1 might possibly be obscured by interstellar absorption, observations were made at Palomar of the reddening of several main sequence stars in the immediate neighborhood of Sco X-1. These observations showed that, if Sco X-1 lies anywhere between 100 and 400 parsec, interstellar absorption in the visible amounts to only 0.7 magnitudes.

Thus a mistaken identification would require (1) that, Sco X-1 is invisible because, against all reasonable expectation, its spectrum decreases with increasing wavelength from the X-ray to the visible region, and (2) that, by an exceedingly unlikely coincidence, an object of the expected magnitude and color characteristics happens to lie within the area of uncertainty for the position of X-ray source.

Further photometric observations and further spectral measurements were made at the Palomar Observatory in July. The object was found to be highly unstable in its continuum radiation changing, on one occasion, from 12.6 to 13.2 magnitude in a 2.6 hour period. The emission lines of hydrogen and He II are present, as well as high excitation lines due to C III, N III and possibly O II. Moreover, the interstellar K line absorption of Ca II is clearly visible. Large changes were observed both in the actual strength of the Balmer lines, and in their strength relative to the continuum.

Searching old plates of the Harvard collection, Garmire and Sreekantan succeeded in tracing the object back to 1896. During the intervening period the object had undergone variations of about one magnitude around a mean value $m = 12.5$, without any indication of a secular trend.(3)

An important question is the distance, D, of Sco X-1. The information on this matter is still quite tentative. As far as I know, no measurement of the parallax has been reported as yet. Johnson and Stephenson have looked for proper motion, and found none, within their accuracy of about 2/100 sec per year.(4) From a measurement of the width of Ca II K-line, and under the assumption of a density of 0.5 atoms per cm^3, Sandage has estimated the distance to be about 260 pc.

Another important question is that of the angular size. Since it is likely that a sizeable fraction of the visible continuum arises from the same process which also produces X-rays, the angular diameter, δ, of the X-ray source should be the same as that of the visible object. Present observations place an upper limit

$$\delta \lesssim 0.5''$$

to this angular diameter.

It is clearly too soon to propose a concrete model for Sco X-1, and I shall not attempt to do so here. I would like, however, to add a few general remarks.

The outstanding property of Sco X-1 is obviously its very large X-ray output. This is about 1000 times greater than its energy output in visible light, comparatively much more than for the Crab, or for any other sources for which a tentative identification with a visible object exists. Thus the primary requirement of the model is that it should explain the large X-ray flux.

As I already noted, the X-ray spectrum suggests bremsstrahlung emission from a hot gas cloud, at a temperature of about 5×10^7 °K. It is therefore worthwhile to examine the consequences of this assumption. For the sake of argument, I have assumed that the source lies at a distance D = 300 pc, and that it subtends an angle $\delta = 0.5''$. I have also taken the X-ray flux of the earth in the 1-10 A region as $F_{1-10} = 5 \times 10^{-7}$ erg cm^{-2} sec^{-1}. Table I lists the assumed parameters as well as some derived parameters, with the indication of how the numerical values of the latter depend on the numerical values of the former.

I would like to call your attention to the rather short cooling time, τ, whose true value is probably considerably smaller than that given in the table, since τ varies as $\delta^{3/2}$. This means that energy must be supplied continuously to the source to maintain its high temperature.

I would like also to note that a cloud of the kind we are considering could be gravitationally contained only if it had at its center a star much more massive than the sun, or if its radius were much smaller than the solar radius. The cloud might be magnetically contained, or at least restrained, by a sufficiently strong magnetic field, anchored to a massive object at its center. The table indicates that, under the assumptions made, the necessary field strength is of the order of two gauss. Since B varies as $\delta^{-3/4}$ this estimate is probably too low.

TABLE I

TENTATIVE PROPERTIES OF SCO X-1

Assumed parameters

Energy flux 1-10 A	$F_{1-10} = 5 \times 10^{-7}$ erg cm^{-2} sec^{-1}
Temperature	$T = 5 \times 10^{7}$ ^{o}K (kT = 4.3 keV)
Distance	D = 300 parsec
Angular diameter	$\delta = 0.5'' = 1/4 \times 10^{5}$ rad.

Derived parameters

Total energy flux	$F = 7.6 \times 10^{-7}$ erg cm^{-2} sec^{-1}	$[F_{1-10}]$
Source power	$P = 8 \times 10^{36}$ erg sec^{-1}	$[F_{1-10}\ D^{2}]$
Source radius	$r = 1.1 \times 10^{15}$ cm	$[D\ \delta]$
Electron density	$n = 0.9 \times 10^{7}$ cm^{-3}	$[F_{1-10}^{1/2}\ D^{-1/2}\ \delta^{-3/2}]$
	$n^{2}V = 4.6 \times 10^{59}$ cm^{-3}	$[F_{1-10}\ D^{2}]$
Source mass	$M = 8.7 \times 10^{28}$ g $\approx 4.4 \times 10^{-5}\ M_{\odot}$	$[F_{1-10}^{1/2}\ D^{5/2}\ \delta^{3/2}]$
Source thermal energy	$W = 3\ nkTV = 10.6 \times 10^{44}$ erg	$[F_{1-10}^{1/2}\ D^{5/2}\ \delta^{3/2}]$
Cooling time	$\tau = W/P = 13.6 \times 10^{7}$ sec $\approx$ 2 yrs.	$[F_{1-10}^{-1/2}\ D^{1/2}\ \delta^{3/2}]$
Min. field for containm.	$B = 2.4$ gauss	$[F_{1-10}^{1/4}\ D^{-1/4}\ \delta^{-3/4}]$

In the absence of gravitational or magnetic containment, the cloud would expand into space at a speed presumably at least as high as the thermal speed of the protons. One would have to assume that, through a suitable mechanism, the cloud is kept at a temperature of the order of 5×10^7 °K up to a certain distance, beyond which it would cool off by adiabatic expansion. With a density of about 10^7, a radius for the hot cloud of about 10^{15} cm, and an expansion velocity of 10^8 cm sec^{-1} the mass loss would amount to 4.0×10^{22} g sec^{-1}, or about 6×10^{-4} solar masses ($M_\odot$) per year. The energy loss would be about 2×10^{38} erg sec^{-1}, or more twenty times greater than the energy output by radiation.

Although the spectrum suggests bremsstrahlung from a hot cloud, it does not rule out other possible mechanisms, in particular synchrotron radiation. In fact it has been shown by Manley(5) that electrons with a rather flat energy distribution that cuts off sharply above some critical energy E_m would indeed produce a synchrotron spectrum approaching an exponential shape. For the observed spectrum, the critical energy E_m is related to the magnetic field B by the equation

$$B E_m^2 = 0.75 \times 10^{23} \text{ gauss}(\text{eV})^2 \quad (1)$$

The rate of energy loss of electrons of energy E by synchrotron radiation is given by equation

$$-\frac{dE}{dt} = 4 \times 10^{-15} E^2 B^2 \quad \text{eV sec}^{-1} \quad (2)$$

If we assume that the number of electrons with energy between E and $E + dE$ is given by $N\,dE/E_m$ for $E < E_m$ and is zero for $E > E_m$, then the total power output of the source per cm^3 has the expression:

$$\frac{P}{V} = 4 \times 10^{-15} \frac{NB^2}{E_m} \int_0^{E_m} E^2 \, dE$$

or

$$\frac{P}{V} = \frac{4}{3} \times 10^{-15} N B^2 E_m^2 \tag{3}$$

Without attempting to specify the model in more detail, I wish to note that, if the magnetic field is sufficiently weak to allow the free escape of the electrons, the "lifetime" of the source is

$$\tau \simeq \frac{r}{c} = 3 \times 10^4 \text{ sec} \quad [DS] \tag{4}$$

On the other hand, magnetic containment of the electrons requires a magnetic field with an energy density at least equal to that of the electrons, i.e., such that

$$\frac{1}{2\mu_0} B^2 = \frac{1}{2} N E_m$$

or

$$N E_m = 5 \times 10^{10} B^2 \tag{5}$$

where E_m is measured in eV and B in gauss.

Combining Eqs. (1), (3) and (5) we obtain:

$$\frac{P}{V} = 1,8 \times 10^{7} B^{7/2} \quad ev\ cm^{-3} \tag{6}$$

With $P \simeq 8 \times 10^{36}$ erg/sec = 5×10^{48} ev/sec and $V = \frac{4}{3}\pi r^3 \simeq$ 5.6×10^{45} cm^3 we obtain

$$B \simeq 6 \times 10^{-2} \text{ gauss} \qquad \left[F^{2/7} D^{-2/7} \delta^{-6/7}\right]$$

$$\bar{E}_m \approx 10^{12} \ eV$$

In this case the "lifetime" of the source is of the order of:

$$\tau \approx \left[E/(-dE/dt)\right]_{E=E_m}$$

or

$$\tau \approx 6 \times 10^{4} \ sec \tag{7}$$

In both cases, therefore, the lifetime is of the order of hours (or less, if $\delta < 0.5''$).

In addition to X-rays and the visible continuum, which may have the same origin, the spectrum of Sco X-1 contains various emission lines, whose study is an important source of information concerning the nature of the object. If we assume that the X-ray source is a hot plasma cloud, the first question that arises is whether the same cloud might possibly be also the source of the observed spectral lines, the mechanism being capture of an electron into an excited state, followed by a transition to a lower state. Let me consider, for example, the H_β line.

An approximate computation shows that the equivalent width of the line resulting from the process described above is about 0.4 A. On the other hand, at the maximum of its luminosity, H_β has an equivalent width of about 6 A. Thus it would seem that the H_β emission from the hot cloud is more than an order of magnitude smaller that it is observed, at least at the times when the line is most brilliant.

There are two additional arguments against the assumption that the hot cloud is the main source of the H_β line. The first is the observation that the strength of the H_β line relative to that of the continuum undergoes large variations. The second is that the width of the H_β line indicates a temperature much lower than 5×10^7 °K.

Thus we are led to the assumption that the source of the hydrogen lines lies in a comparatively cool region. If the X-ray source is a hot cloud, the cold region may be located inside this cloud, or it may surround it. If the x-radiation arises from a synchrotron process, the cool gas responsible for the line spectrum may occupy the same volume as the high-energy electrons responsible for the X-ray emission. In any case, it is certain that the cool gas is immersed in an exceedingly strong flux of ionizing radiation. This is $(2/\delta)^2$ times stronger than the flux observed at the earth, and thus amounts to at least 5 x 10^5 erg cm^{-2} sec^{-1}. Thus unless the cool gas has a very high density, it must be almost 100 percent ionized. Which means that the origin of the line spectrum must be fluorescence induced by the X-ray flux rather than collisional excitation. If this is so, the power emitted, for example, in the H_β line has the expression

$$P_{H\beta} = (n^2 V)_{cool}\, \alpha_{42}\, (h\nu)_{H\beta}$$

where α_{42} is the effective capture coefficient leading to the H_β emission. An approximate computation, based on the assumption that the temperature of the cool region is 5 x 10^4 °K, shows, that, in order to account for the intensity of the H_β line (when its equivalent width is 6 A), the ratio $(n^2V)_{cool}$ to $(n^2V)_{hot}$ must have a value of the order of

$$\frac{(n^2V)_{cool}}{(n^2V)_{hot}} \approx 6 \times 10^{-4}$$

We may, for example, make a model, admittedly unrealistic, assuming that the hot cloud is a sphere of radius $r = 10^{15}$, and the cold cloud is a shell of thickness x surrounding this cloud. If we assume, moreover, that the two clouds have the same density, we find

$$x = 2 \times 10^{-4}\, r = 2 \times 10^{11}\ \text{cm}$$

The optical depth of such a shell turns out to be smaller than unity at the Lyman edge and greater than unity for the Lyman lines.

Another question is whether a sizeable fraction of the visible continuum may originate from the same cool cloud which is the source of the line emission. The ratio between the energy going into the continuum to the energy going into the H_β line must be of the order of the ratio between to total recombination coefficient to α_{42}, which ratio is approximately 10. On the other hand, the energy in the visible continuum is about 500 times that in H_β, when H_β is strongest, and much more at other times. Therefore it seems that the bulk of the continuum must come from the "hot" region.

There are several other pieces of information that I have not yet discussed.

One is the presence of the lines of He II, C III, N III. Can these high-excitation lines come from the same region where the Balmer lines of hydrogen originate?

Another piece of information is a recent result of Friedman's group, according to which the energy flux from Sco X-1 in the 44 to 60 A region is about 10^{-7} erg/cm^2 sec.(6) This is about 8 times the flux expected on the basis of the observations in the 1 to 10 A region. Moreover, even if the source were as close as 100 parsec, the optical depth of interstellar matter between us and Sco X-1 (computed for $n = 0.5$) would be unity at 44 A and 3 at 60 A. Thus the discrepancy between the observed and the predicted value amounts at least to a factor of the order of 50. I feel that it would be very desirable to check Friedman's results, possibly by a more direct method than the two-color photometry used by his group. If these results are confirmed, one would have to accept Friedman's conclusion to the effect that Sco X-1 contains, in addition to the "hot" and the "cool" plasma clouds, also an optically thick object (possibly a neutron star) at a temperature of about 2 million $^{\circ}$K.

I would like to conclude by mentioning a number of observations potentially capable of shedding light on the nature of Sco X-1.

1. Most important is a search for possible time variations in the X-ray flux, and, if such variations are found, a study of their correlation with the variations in the visible continuum and in the various lines.

2. In order to improve on our present meager knowledge of the distance of Sco X-1, an attempt should be made to measure its parallax. Also, it may be possible to obtain a better estimate of the proper motion than is presently available.

3. It would be most desirable to determine the angular diameter of the visible object, or to reduce the upper limit below the present value 0.5". Many important properties of Sco X-1 are critically dependent on δ .

4. A search should be made for a possible polarization of the visible continuum; a positive result would, of course, provide evidence for synchrotron emission.

5. I imagine that many additional valuable data will soon be forthcoming from more careful observations of the optical emission lines and from an extension of these observations into the infrared and ultraviolet. For example, are there forbidden lines? If not, can this be taken as an

indication for a high density in the source region? Or can the absence of forbidden lines be explained by the high flux of ionizing radiation in which the source is immersed?

6. If at all possible, one should look for emission lines in the X-ray region. As emphasized by Schklowskii at the recent Symposium in Noordwijk, particularly significant would be the detection of the Fe 24 and Fe 25 lines, which begin to appear prominently only at temperatures of the order of 50 million ^{o}K.

7. Finally it is to be hoped that accurate determinations of the positions of other X-ray sources will soon disclose whether other objects similar to Sco X-1 exist. The rate of occurrence of celestial objects with the peculiar properties of Sco X-1 will provide a clue as to whether or not a situation where most of the radiated energy appears in the form of X-rays represents a common phase in the stellar evolution.

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FIGURE CAPTIONS

Fig. 1 Schematic diagram of the collimators and counters used by the ASE-MIT group to determine the angular size and the location of celestial X-ray sources (see Refs. 1, 2).

Fig. 2 Photograph of the collimators represented schematically in Fig. 1.

Fig. 3 Transmission of a modulation collimator as a function of angle in the direction perpendicular to the transmission bands (see Ref. 1).

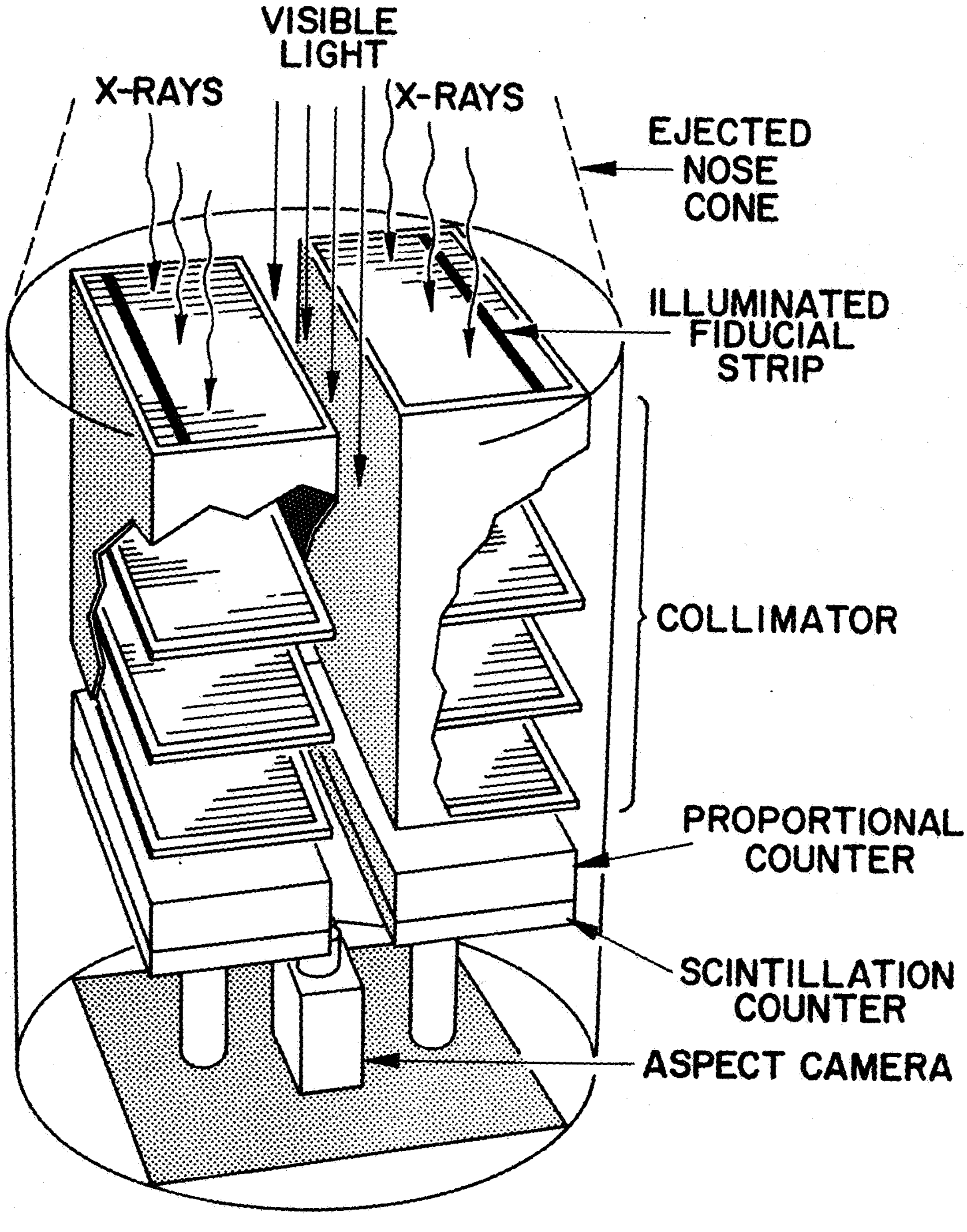
Fig. 4 Two photographs of star field and transmission bands of the collimators obtained during the rocket flight of the ASE-MIT group (see Ref. 1).

Fig. 5 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 (see Ref. 1).

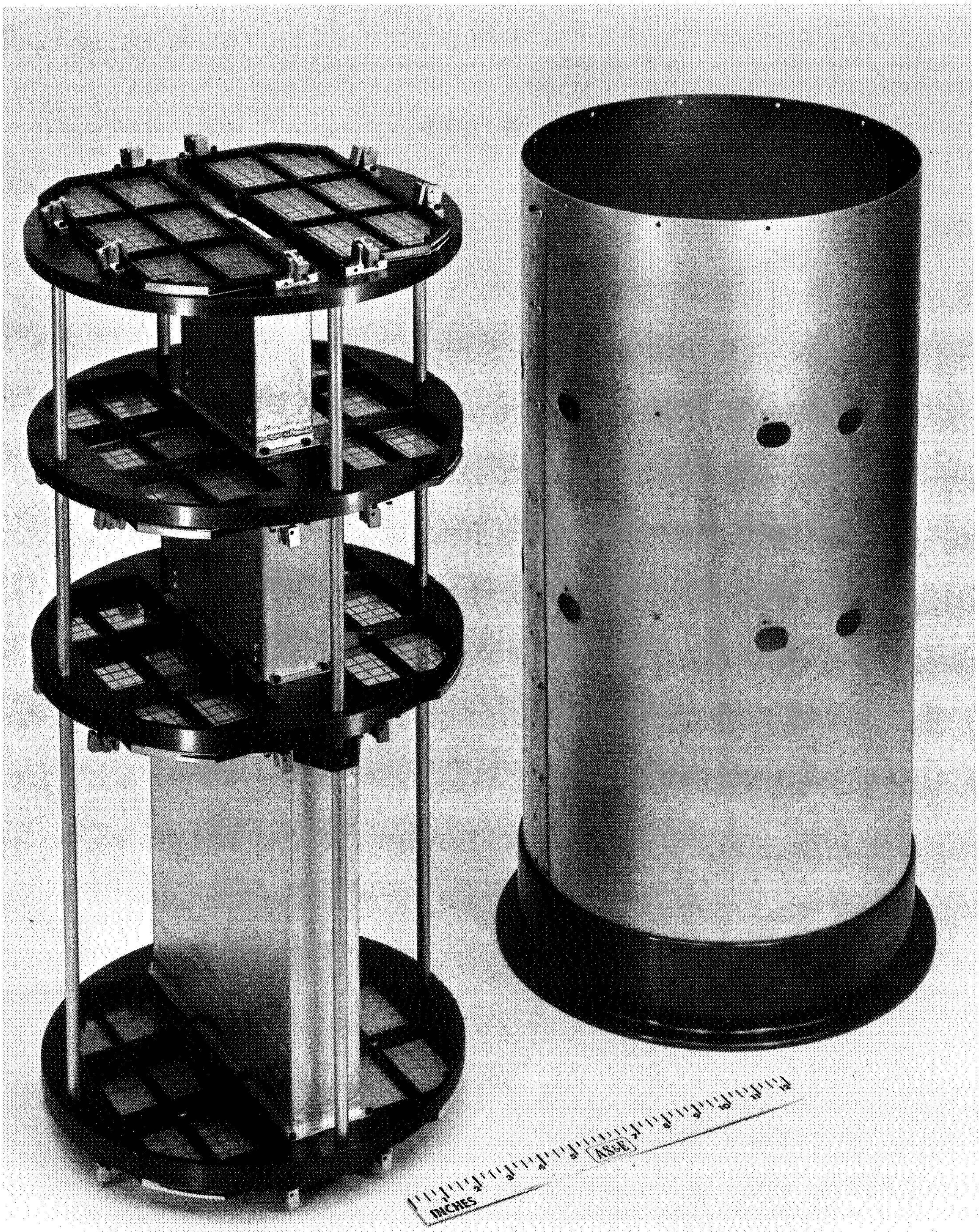
Fig. 6 Superposition of the data corresponding to several peaks such as those shown in Fig. 5.

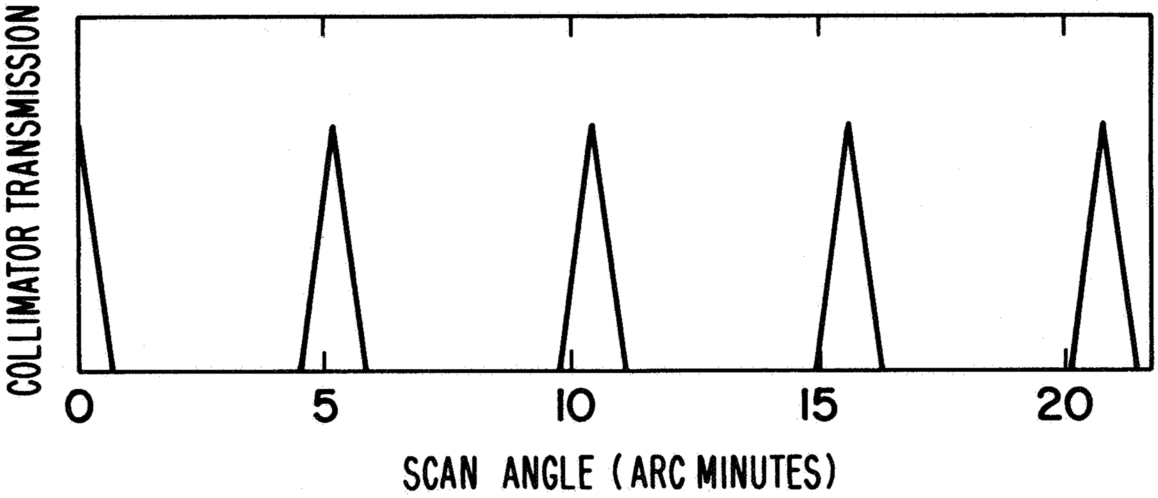
Fig. 7 The location Sco X-1. The results obtained during the rocket flight discussed here are compared with those from previous experiments (see Ref. 2).

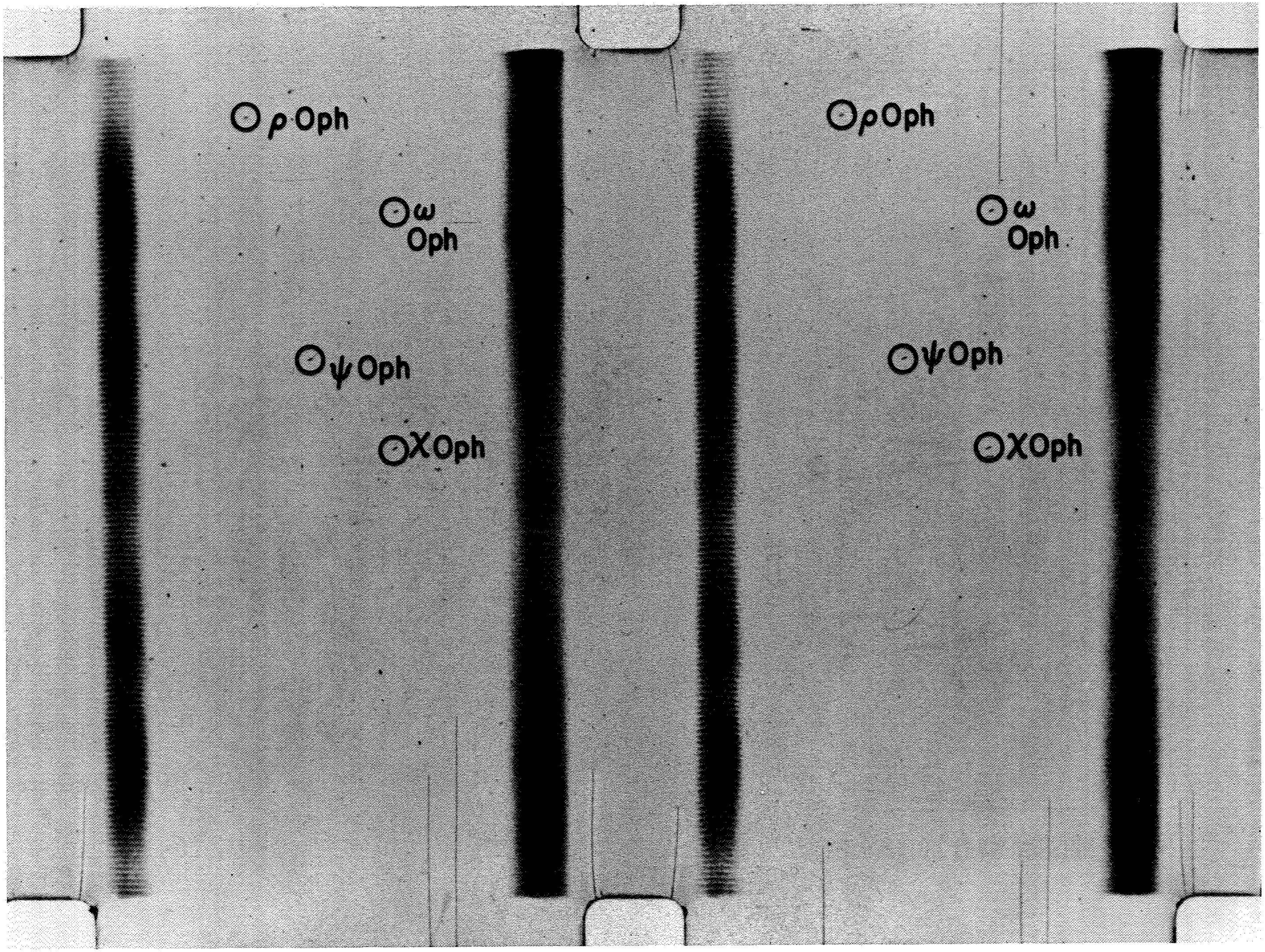
Fig. 8 Photograph of the region containing the new X-ray position of Sco X-1, reproduced from the Palomar Sky Survey prints. The two equally probable X-ray positions are marked by crosses surrounded by a rectangle of 1 by 2 arc min. The object described in the text is marked with an arrow. The identifications of other stars for which photoelectric photometry exists are also marked (see Ref. 3).



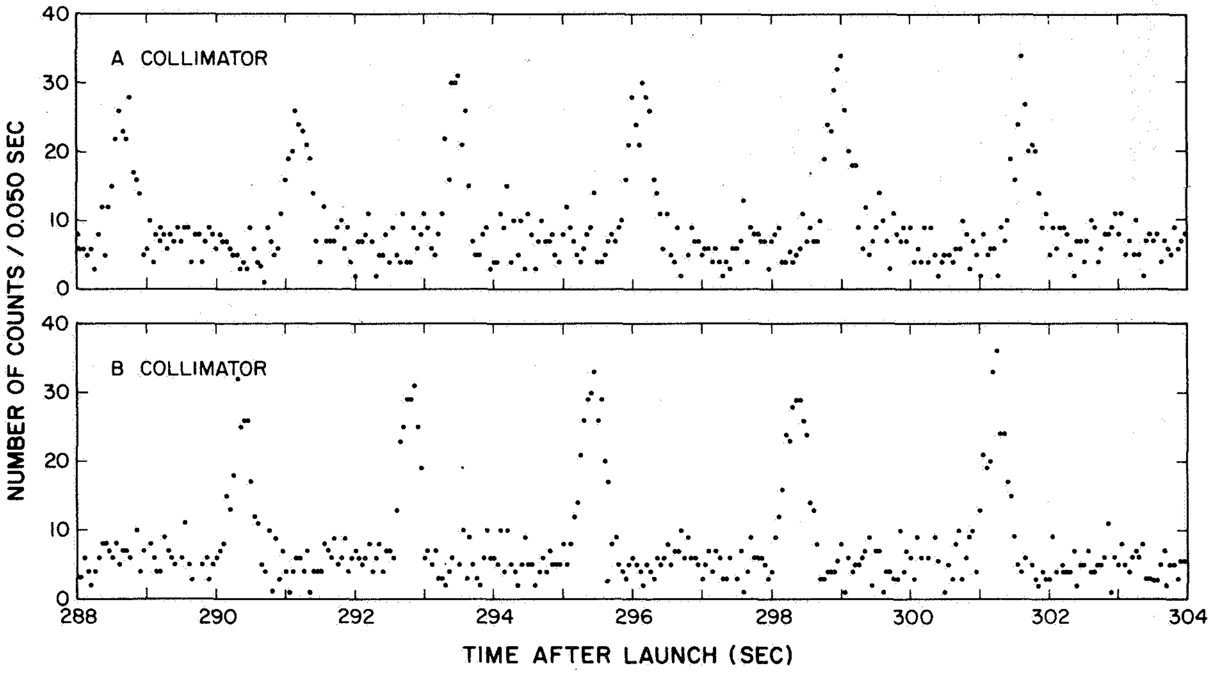
VISIBLE LIGHT
X-RAYS
X-RAYS
EJECTED NOSE CONE
ILLUMINATED FIDUCIAL STRIP
COLLIMATOR
PROPORTIONAL COUNTER
SCINTILLATION COUNTER
ASPECT CAMERA


INCHES
AS&E

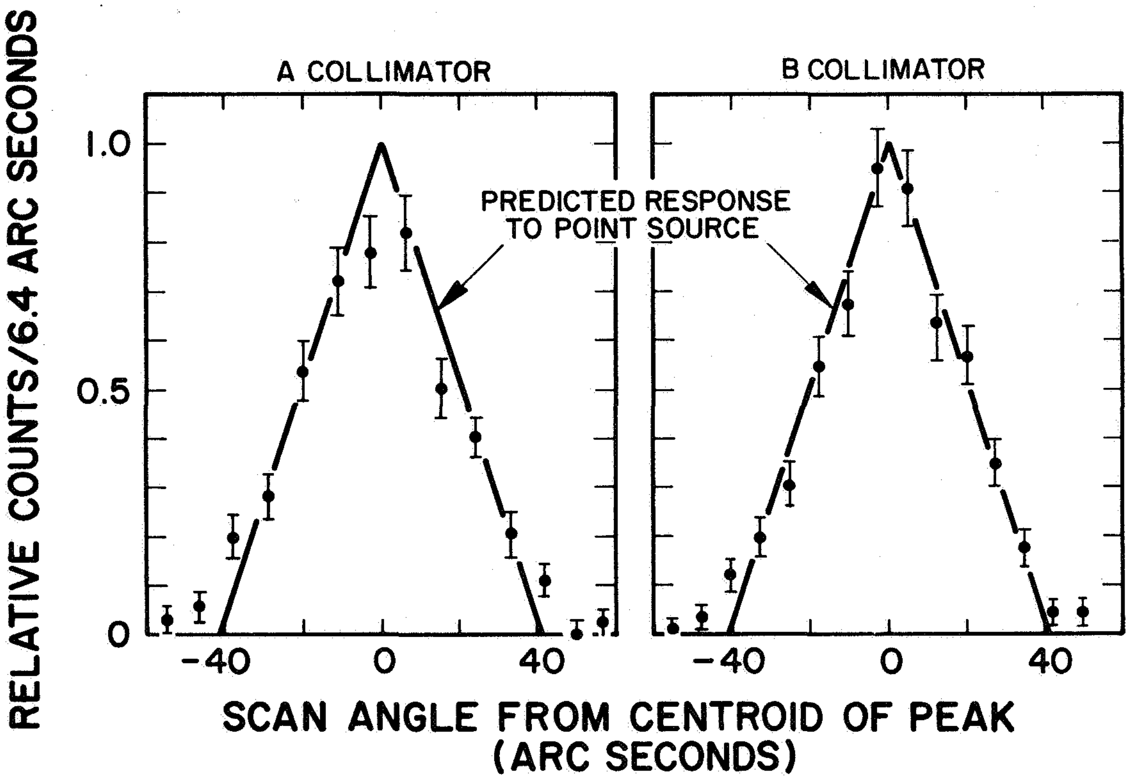

COLLIMATOR TRANSMISSION
0
5
10
15
20
SCAN ANGLE (ARC MINUTES)

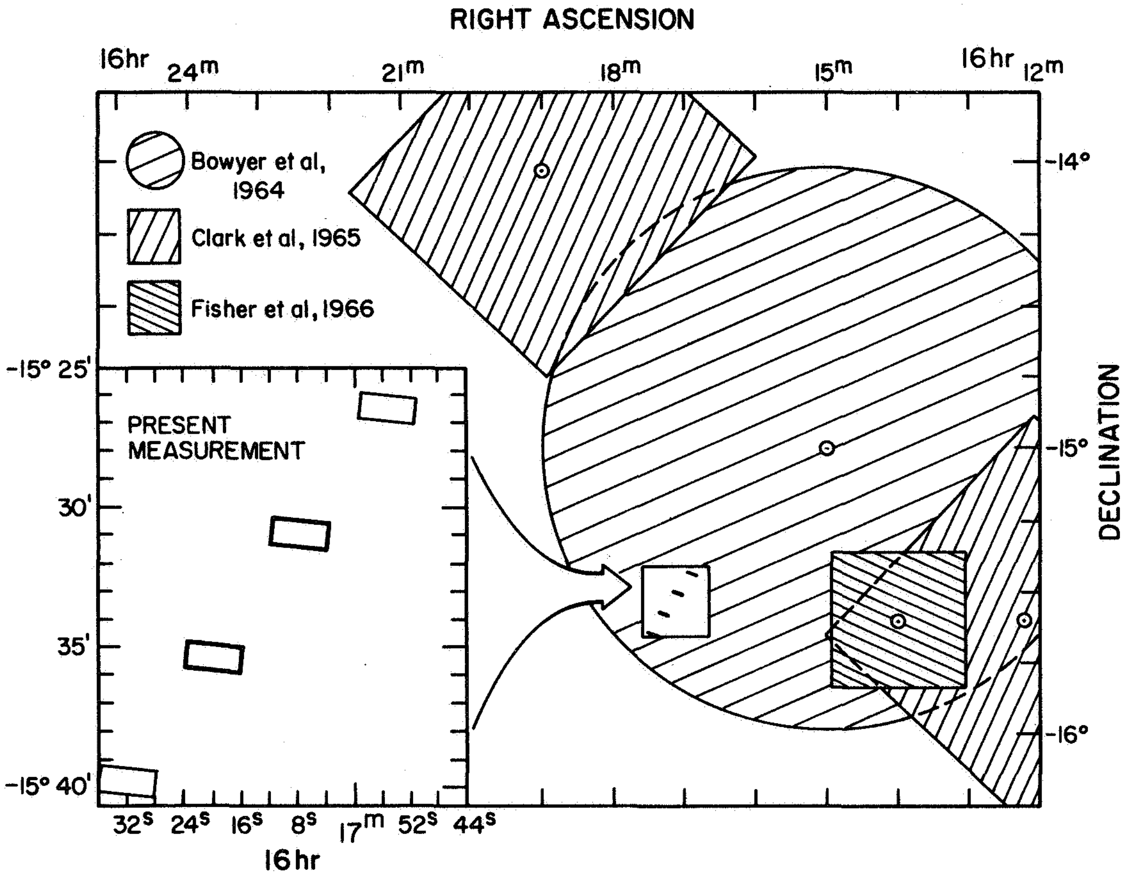


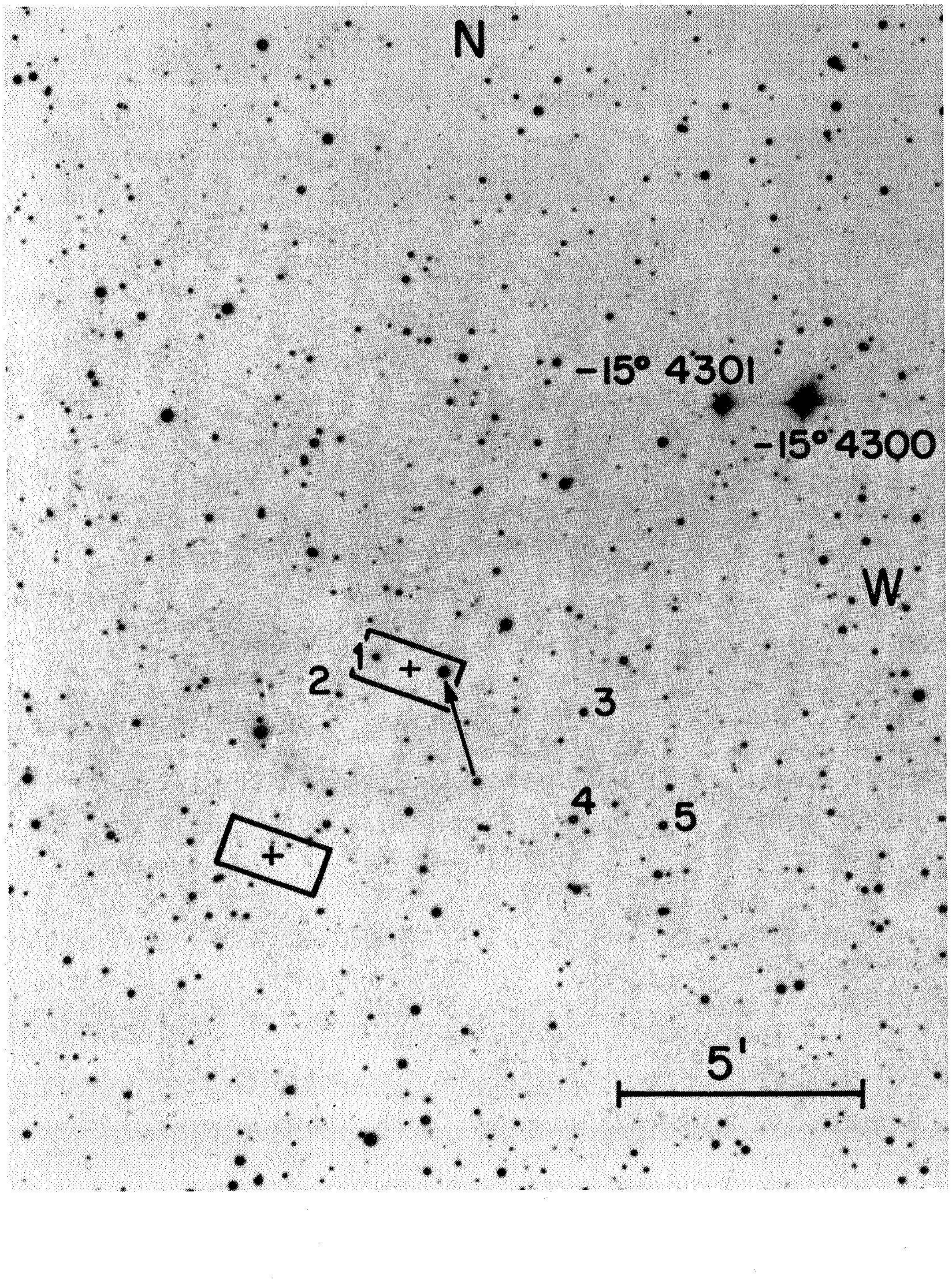
ρ Oph
ω Oph
ψ Oph
χ Oph
ρ Oph
ω Oph
ψ Oph
χ Oph



A COLLIMATOR
B COLLIMATOR
40
30
20
10
0
NUMBER OF COUNTS / 0.050 SEC
288
290
292
294
296
298
300
302
304
TIME AFTER LAUNCH (SEC)


A COLLIMATOR
B COLLIMATOR
RELATIVE COUNTS/6.4 ARC SECONDS
1.0
0.5
0
PREDICTED RESPONSE TO POINT SOURCE
-40
0
40
-40
0
40
SCAN ANGLE FROM CENTROID OF PEAK (ARC SECONDS)


RIGHT ASCENSION
16hr 24m
21m
18m
15m
16hr 12m
Bowyer et al, 1964
Clark et al, 1965
Fisher et al, 1966
-14°
-15°
-16°
DECLINATION
-15° 25'
30'
35'
-15° 40'
PRESENT MEASUREMENT
32s 24s 16s 8s 17m 52s 44s
16hr


N
−15° 4301
−15° 4300
W
1
2
3
4
5
5'