ASE-1762

FINAL REPORT

RESULTS OF A SOUNDING ROCKET EXPERIMENT TO STUDY GALACTIC X-RAY SOURCES

Contract NASW-1583

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FOREWORD

This document is the final report on contract NASW-1583 which called for the reduction and analysis of data obtained from NASA Aerobee 4.149 which was flown from White Sands Missile Range on 11 October 1966. The rocket payload was developed at AS&E under NASA contract NASW-1505. The rocket payload was capable of performing a moderate angular resolution scan for X-ray sources and of recording the position of the sources and the spectral content of the detected X-rays. The objective of the flight was to scan the Milky Way between galactic longitudes -20° to $+90^{\circ}$. The bulk of the observational time was spent in scanning the Cygnus region centered at longitude 80°. The authors of this report are R. Giacconi, P. Gorenstein, H. Gursky, P. Usher and J. Waters.

ACKNOWLEDGMENTS

A part of this work represented a joint effort with scientists at the Mount Wilson and Palomar Observatories. The participating scientists were Professor A. Sandage, Dr. P. Osmer and Dr. J. V. Peach. Results of this joint effort have been reported in the June, 1967, issue of the Astrophysical Journal.

We wish to acknowledge the support in this work of 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. Additional computational and programming work was performed by Mr. R. Talbot and Mr. J. Silk.

We also wish to acknowledge many fruitful discussions with Dr. M. Annis, Dr. J. Carpenter and Dr. O. Manley of AS&E, Professor Bruno Rossi of MIT and Dr. Gordon Garmire of California Institute of Technology.

INTRODUCTION

The results presented here are the continuation of an observational program of X-ray astronomy that began at AS&E in 1961. The present experiment was performed from an Aerobee rocket flown from the White Sands Missile Range on 11 October 1966. The payload was developed under contract NASW-1505 and has been described in the final report on that contract in NASA document CR-752 (April, 1967). The experiment plan is also described in that document.

The status of X-ray astronomy at the time that this rocket experiment was planned can be described as follows:

1. The strong source Sco X-1 had been identified with a faint blue star-like object (1).

2. It was reported that X-ray sources coincided with Cygnus A and M-87, the well-known extragalactic radio sources (2).

3. The remaining X-ray sources were reported to be concentrated along the Milky Way with a possible correlation with spiral arms (3, 4).

The objectives of the present experiment were chosen to obtain information on the nature of the galactic X-ray sources. In the first place, we wished to determine whether any X-ray sources could be identified with optical objects, such as the one associated with Sco X-1. In the second place, we wished to localize, with moderate resolution, the X-ray sources that are grouped in the Sgr-Sco region of the Milky Way. Third, we wished to obtain spectral information on the X-ray emission of the sources.

The Cygnus region of the sky was chosen as the primary area to be observed for the following reasons:

1. The region contained two relatively strong and isolated X-ray sources, Cyg X-1 and Cyg X-2.

2. The region contained Cyg A, one of the reported extragalactic X-ray sources.

3. Cygnus is favorably situated for optical observations from the Northern Hemisphere; and one of the known X-ray sources, Cyg X-2, was about 10° off the Milky Way, making it more accessible to observation than other X-ray emitters.

The rocket payload used to carry out these objectives contained beryllium-window proportional counters to detect the X-rays, narrow field-of-view collimators to isolate the X-rays, and a camera to photograph the star field to determine vehicle attitude. The rocket, itself, was equipped with a gyroscope-referenced attitude control system (roll-stabilized ACS) which permitted the scan of selected regions of the sky at controlled rates. This control system was utilized to scan the Milky Way from Sagittarius to Cygnus in a single, continuous sweep and to then crisscross the Cygnus region. The latter comprised the major fraction of the available observation time. In scanning Cygnus, the maneuvers were arranged to maximize the time spent on Cyg A, Cyg X-1 and Cyg X-2. In addition, in order to allow good location determinations, the objects were traversed along several different scan lines.

The reduction of the flight data was accomplished using techniques developed for earlier rocket flight data. Individual pulses from the proportional counters were recorded on paper records. The time and amplitude of each recorded count were punched onto cards for use on an IBM 1620 computer. The computer was used to sort the individual counts according to various time and amplitude intervals. Star positions were recorded from enlargements of the flight film that recorded the star field. A computer program was used to analyze these positions to yield the rocket attitude on a second-by-second basis. Additional analyses involved drawing the position of the X-ray detector axes on the celestial sphere at particular times, determination of the transit time of the detected X-ray sources by fitting the known angular response function of the collimators to the actual data, and analysis of the spectral content of the detected X-rays.

This effort has resulted in the publications that are incorporated as appendices to this report. The principal results and conclusions are listed below, grouped according to the papers in which they appear.

I. ASE-1587 - An X-ray Survey of the Cygnus Region.

The positions of four X-ray sources were presented, of which two had not been previously reported. Cygnus A was not observed to emit X-rays; the upper limit on its intensity was about 1/5 that reported earlier. No other X-ray sources were observed in the Cygnus region with an intensity greater than between 1/100 and 1/200 that of Sco X-1. One of the detected X-ray sources, Cyg X-3, was centered within the Cygnus X radio complex. None of the recorded X-ray sources coincided with any outstanding single objects in the area.

II. ASE-1610 - On the Optical Search for the X-ray Sources Cyg X-1 and Cyg X-2.

In collaboration with the Mount Wilson and Palomar Observatory the positions reported in ASE-1587 for Cyg X-1 and Cyg X-2 were searched for optical objects that might be the X-ray sources. A candidate object was found for Cyg X-2 that has many of the optical properties of Sco X-1. No candidate optical object was found for Cyg X-1; however, the region is badly obscured and the optical counterpart may be highly reddened or even invisible. Subsequent investigations (5, 6, 7) of the candidate for the optical Cyg X-2 have revealed that object as highly peculiar in its own right and lends support to the possibility that it is, in fact, the X-ray source.

III. ASE-1712 - The Distribution of Galactic X-ray Sources from Scorpio to Cygnus.

Positions of 17 X-ray sources were presented based on data obtained from the experiment. Of these, four positions were those presented in ASE-1587; six of the positions were for X-ray sources not previously reported. These positions were precise to within from 10 to 15 arc minutes in galactic longitude. Except for the Cygnus sources, positions in galactic latitude were uncertain to the order of degrees. These positions showed an apparent correlation with extreme population I objects such as HI and HII regions, as opposed to correlating with population II objects such as old novae.

IV. ASE-1713 - The Spectra of Several X-ray Sources in Cygnus and Scorpio.

The spectra of the observed X-rays from a number of the sources observed during this experiment were presented. These spectra were analyzed in terms of a number of the popular theoretical models for X-ray sources. The outstanding feature of these data was that several of the spectra showed a deficiency of photons at low energy that could only be interpreted as absorption effects, possibly by the interstellar medium or within or adjacent to the X-ray sources themselves. The largest deficiency was noted in Cyg X-3, the source that is centered within the Cygnus X region. It thus coincides with the tangential direction of the Cygnus spiral arm which, from 21 cm radio studies, is known to be a region of particularly high neutral hydrogen density; and it is plausible that the effect is indeed one of interstellar absorption, although other possibilities cannot be excluded.

These results, along with earlier work by AS&E and other groups, have established the existence of X-ray sources as well-defined galactic constituents. Some, but not the majority, are supernovae remnants. The majority may belong to the class of objects characterized by Sco X-1 and Cyg X-2. Of course, there may be additional classes of X-ray sources. The major questions regarding the nature of these objects have yet to be answered, by this we mean, the mechanisms by which the X-rays are generated, the source of energy for the X-rays, and, finally, where the X-ray sources fit with respect to other objects in the galaxies; namely, from what conditions did they evolve and to where are they evolving.

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APPENDIX A

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ASE-1587

AN X-RAY SURVEY OF THE CYGNUS REGION

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AN X-RAY SURVEY OF THE CYGNUS REGION

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In order to localize and identify X-ray sources, we have scanned the Cygnus region with large area proportional counters flown on an attitude controlled sounding rocket. We find four X-ray sources in the region between $70^{\circ} \leq \ell^{II} \leq 100^{\circ}$, $-16^{\circ} \leq b^{II} \leq +10^{\circ}$ for which we have derived locations precise to about 10 arc minutes. Two of these sources, the most intense, were previously known; we report the two others as new sources, although they may have been observed previously in coarser surveys. The scanned region included Cyg A, the strong, extragalactic radio source, which is not observed to be an X-ray source. An optical search of two of the regions (described in the accompanying letter, Giacconi, Gorenstein, Gursky, Usher, Waters, Sandage, Osmer and Peach, 1967) has revealed an object at the location of the source Cyg X-2 which has visible light characteristics similar to those of the optical counterpart of Sco X-1 (Sandage, Osmer, Giacconi, Gursky, Waters, Bradt, Garmire, Sreekantan, Oda, Osawa, Jugaku, 1966; Johnson and Stephenson, 1966). Another of the X-ray sources is in the Cygnus X radio region and along the Cygnus spiral arm. During the early portion of the same rocket flight, the region $-20^{\circ} \leq \ell^{II} \leq 70^{\circ}$, centered at $b^{II} = 0^{\circ}$ was scanned and included the observation of Sco X-1. The data gathered in that region will be discussed in a forthcoming paper.

The existence of X-ray sources in Cygnus is already well established. The very first observations of celestial X-ray sources by Giacconi, Gursky, Paolini, and Rossi (1962) in June 1962, in conjunction with observations by the same group in October 1962, indicated the existence of a source in Cygnus (Gursky, Giacconi, Paolini, and Rossi, 1963). Subsequently, Bowyer, Byram, Chubb, and Friedman (1965) of the Naval Reserach Laboratory (NRL), reported observing two X-ray sources in Cygnus during a June 1964 rocket flight; Fisher, Johnson, Jordan, Meyerott, and Acton (1966) of Lockheed reported seeing a single source during an October 1964 flight, and Byram, Chubb, and Friedman (1966) reported 4 sources based on an April 1966 rocket flight, one of which was identified as Cygnus A. By comparing the data obtained during the June 1964 and April 1965 flights, Byram et al. (1966) reported that the source denoted as Cyg XR-1 had undergone a fourfold change in intensity. The locations of the sources as reported by the two groups are summarized in Figure 1. Other groups have also explored the Cygnus region with balloon and rocket-borne instrumentation to measure the spectra of the X-ray radiation originating in these regions, but with angular resolution too coarse to distinguish and locate discrete X-ray sources. Except for the identification of Cyg A, which now appears to be incorrect, none of the X-ray sources has been associated with visible or radio objects.

There were several reasons that made the Cygnus region an interesting one for observation. First, we wished to test our working hypothesis that many of the known galactic X-ray sources are similar in their optical characteristics to Sco X-1. The X-ray sources in Cygnus appear to be isolated and, thus, easier to localize than those near the galactic center where the X-ray source density is much higher. Second, the region contains many interesting visible and radio objects that might be X-ray sources; e.g., old novae, to which a connection is suggested by a current interpretation of the optical data on Sco X-1. Finally, as noted, Cyg A had been reported to be an X-ray source at a power level that greatly exceeded the visible and radio emission from the galaxy. Such an observation clearly required verification.

The instrumented rocket utilized to achieve these objectives was an Aerobee 150, flown from the White Sands Missile Range on 11 October 1966. The X-ray detectors were argon-filled, beryllium window proportional counters with an effective area of about 800 cm^2. The low energy cutoff (counter efficiency $<$ 25%) was about 1.5 keV and was determined by the thickness of the beryllium window of 9.1 mg/cm^2. The high energy cutoff was about 12 keV and was determined by the gas filling of argon which had an equivalent thickness of 9.0 mg/cm^2. The energy resolution of the counters was 21%, full width half maximum (FWHM) for 5.9 keV X-rays. Counter signals originating from penetrating particles were eliminated by the use of a veto signal from a group of guard counters. All other signals were telemetered to the ground with their amplitudes preserved; however, only those signals corresponding to energies between 2 and 5 keV were used in the analysis leading to the location of the sources.

The detectors were arranged with two different fields of view corresponding to what will be referred to as the (A + C) and the (B + D) counters. The shapes and dimensions of the two fields were identical ($1^\circ \times 40^\circ$, FWHM) but did not exactly overlap. The centers were displaced by 20° from each other along the direction of the 40° dimension, as shown in Figure 1. Thus, a source traversal would appear simultaneously in the two sets of detectors, but the peak counting rate would be different depending on the location of the X-ray source within the field of view as the source was being traversed.

The observations were made by slowly traversing the Cygnus region along several different scan lines which were obtained by having the rocket maneuver between fixed points in the sky at preset rates. These lines (see Figure 1) represent the position of the center of the field of view of the combined detectors. The long dimension of the fields of view was approximately perpendicular to the scan lines. Thus, along lines 1, 2, 3 and 4, a band of sky $\sim 40^{\circ}$ width was scanned. The average rate of scan along these lines was 0.4°/sec, 0.23°/sec, 0.5°/sec, and 2°/sec respectively. To make the change in orientation required to go from line 1 to line 2 and from line 3 to line 4, the rocket was rotated about points A and B respectively. During these rotations, a portion of a circular sector of $\sim 40^{\circ}$ diameter was scanned. To make the change required to go from line 2 to line 3, the rocket was rotated in such a way to carry the X-ray axis in the direction of the long dimension of the X-ray field of view. The purpose of this maneuver was to reposition the detector axis in preparation for the scan along line 4.

The instantaneous attitude of the vehicle was obtained by photographing the star field at a 1 second rate with a 16 mm camera that was equipped with a f/0.9, 25 mm focal length lens. The field of view of the camera overlapped that of the X-ray detectors. The magnitude of the faintest detectable stars was a function of the scan rate, and varied from about +3 mag to +6 mag. The orientation of the film plane was found by reference to a minimum of four stars in each frame. Whenever possible the validity of the orientation measurement was determined by comparing the calculated position on the film of those stars not used in the analysis with their measured position. The deviations between the two were typically 2 arc minutes and represent the reading error on the individual stars. The calculated orientation of the film plane, since it was based on measurements of a number of stars, should be better than this; in fact, the scatter in the curve that connects consecutive measurements of orientation (i.e., the scan line) was less than 1 arc minute. The relative orientation of the X-ray detectors with respect to the film plane was determined by a pre-flight survey that utilized parallel beams of light and X-rays.

The X-ray data obtained during the times corresponding to the scans shown in Figure 1 are plotted in Figure 2. A number of peaks, each corresponding to the transit of an X-ray source, appears in the data. A peak was defined as a one degree region (i.e., one resolution element) in which the observed number of counts exceeded the expected background counts by at least three times the square root of the observed counts (3σ). The background level was obtained during the interval of 230 - 255 sec, a time when the detectors were viewing a region removed from the galactic equator and where no sources are apparent. The background, which mostly results from gamma-rays and the inefficiency of the anticoincidence counters, as well as a contribution from the isotropic X-ray background, was sensitive to the orientation of the vehicle and was observed to change slowly by about 20% during the flight. These changes did not significantly affect our ability to select the peaks. As noted earlier, because of the offset of the detector axes, the peaks do not appear with the same intensity in the two sets of detectors. For example, the peak marked g appears much stronger in (A + C) than in (B + D), and the strong peak i in (A + C) does not appear at all in (B + D). The data are plotted as a function of time and the widths of the peaks vary according to the instantaneous rate of scan; e.g., peak a is much narrower than peak g. The actual angular widths are roughly as expected on the basis of the known angular response of the detectors to X-ray sources with angular sizes smaller than the angular resolution.

The data represent a series of one dimensional scans across a region that is known to contain a number of discrete sources. Each peak in the data defines a line of position (actually the arc of a great circle) on which the source must lie. The relative counting rates in the two sets of detectors restricts the source position to a portion of the line of position; precise location is obtained from the intersection of two or more lines obtained during the several scans at different orientations. The locus of possible source positions for all the peaks in Figure 2 are drawn in Figure 3. The problem of pinpointing the sources is to find a unique set of locations that agree with the data. Not only must the sources be at the intersections of two or more lines of position, but the locations must also yield the correct relative source intensities as seen in the several traversals. We also keep in mind the possibility that a weak source may be masked by a strong source. On this basis, the 14 lettered peaks have been reduced to 5 sources, as shown in Figure 3, and discussed in the following paragraphs. For convenience, we denote the sources as S-1, S-2, etc.

<u>S-1</u> This source is at the intersection of lines a, g and i. The greater intensity of peaks g and i in (A + C) than in (B + D) indicates a position south of scan line 2. Peak e is apparently also caused by S-1. It occurs during a time when the rocket made a transition from one maneuver to another and was undergoing a rapid excursion compared to the normal scan rates. The line of position corresponding to e was not as precise as the other lines and was not drawn.

<u>S-2</u> This source is at the intersection of lines d, l and m, a location that is consistent with peak d appearing in (B + D) but not (A + C).

S-3 This source is at the intersection of lines b, f and j. The position is consistent with these three peaks being of comparable intensity in the two detectors. The doubling observed for peak b is a result of the source actually being traversed twice within a short time. As with e, this peak occurs at a time when the rocket was switching between maneuvers and the motion was not steady. However, the star photographs allowed us to plot the motion in detail, and the line of position could still be drawn with only a slight loss of precision.

S-4 The small peaks c, k and n appear to have a common intersection within the expected errors which we use to define this source. Its intensity is close to the limit of sensitivity of this survey. The peak c appears only in counters (B + D) which is consistent with the source location. Peak c cannot be part of peak b (S-3), the correct shape of which can be seen in (A + C). The peak n does not meet the 3σ requirement in each of the counters. At this time the rocket was beginning to re-enter the atmosphere, as shown by the decreasing background, so that the decrease in intensity is as expected. Peak n was not used to determine location. Alternate interpretations are possible for peaks for c, k, n; the interpretation that we have chosen is the simplest one that accounts for the data. It is possible to interpret these peaks in terms of more than one source located in the scan region. This implies that certain count rate peaks are missing from the data, either because the peak due to the source is obscured by the presence of a strong source, or that the peak does not meet the 3σ requirement.

S-5 This source shows up only as peak h in (A + C). Since it does not appear in (B + D) nor along scan line 1, it must be well south of scan line 2 and not consistent with being masked by peak a. It is apparently the result of a source outside the Cygnus region at around $\ell^{II} = 50^{o}$ and observed earlier than 130 sec. These data will be discussed in a forthcoming paper.

The sources for which two or more intersections are obtained are listed in Table I along with their intensity and location, the location always being taken as the intersection of the two more precise lines of position. In each case the third line of position was consistent with the derived location. We also assign a name to each source in accordance with the nomenclature we first adopted in reporting X-ray sources in December 1964, (Giacconi, 1964). The size of the error boxes for each location was determined from the uncertainty in drawing the individual lines of positions. There are several sources of possible error, namely, the precision of the alignment between the camera and the X-ray fields of view, the knowledge of instantaneous orientation as found from the star photographs, and the determination of the exact time of transit of the X-ray source in the counters. The largest of these was the last. The actual transit time was found by fitting the measured response curve of the collimator to the observed data, and the error in transit time was determined from the χ^2 variation as the peak time was varied. In each case the several errors were combined in quadrature. We have considered the possible systematic errors which may affect this measurement. The largest systematic error that we can evaluate stems from the uncertainty in the laboratory measurement of the relative position of the field of view of the X-ray detectors with respect to the film plane of the aspect camera. If the spread between the several measurements that were made of this quantity is interpreted as a true displacement, rather than simply the random scatter around a mean value, we find that there may be present a 2' systematic error. Accordingly, this amount was added directly to the uncertainties in drawing lines of position to give the resulting error boxes shown in Figure 3.

The source positions are shown in Figure 1 along with the results of earlier measurements carried out in the Cygnus region. Cyg X-1 and Cyg X-2 agree with earlier reported locations for X-ray sources in the region. We find the two to be of comparable strength, although of somewhat lower intensity than reported by Byram et al. (1966) who also find the two to be of near equal strength based on their April 1965 flight. The source Cyg X-3, which is about 1/3 the intensity of Cyg X-2 (we will discuss intensities relative to Cyg X-2 rather than Cyg X-1 which, as noted earlier, may be variable) has not been reported by either Byram et al. (1966) or Fisher et al. (1966).

We do not see Cyg A as an X-ray source. This object was traversed three separate times as shown in Figure 2. Summing the data from these transits yields a counting rate above background of 0.004 ± 0.01 cts/cm^2-sec in the 2 to 5 keV region. The upper limit (3σ) for the intensity of Cyg A is thus 0.03 cts/cm^2-sec, about 1/15 of Cyg X-2. We also examined the data in the 5 - 7 keV energy range. We find a counting rate above background of $11 \pm 8 \times 10^{-3}$ cts/cm^2-sec in the region of Cyg A which is 1/6 that observed from Cyg X-2 in the same energy range and consistent with zero. We conclude that our data are inconsistent with those reported by Byram et al. (1966), who report the X-ray emission from Cyg A to be about 0.4 of Cyg XR-2, the source that we denote as Cyg X-2. The earlier identification of Cyg A as an X-ray source was based on an unresolved peak adjacent to Cyg XR-1, which it may be possible to interpret in terms of a source at another location, perhaps Cyg X-3.

We do not see Cyg XR-4 or Vul XR-1. The former is reported to have an intensity 1/3 Cyg XR-2, which we could not have failed to detect (c.f., peaks b, f or j in Figure 3 which correspond to the same relative intensity). Cyg X-4 is within the area of uncertainty of this source, but its intensity is found to be only 1/9 of Cyg X-2. Vul XR-1 may be masked by Cyg X-1 on scan line 1 and too weak to be seen on scan line 3.

We turn now to the nature of the X-ray sources themselves. Only two sources have been positively identified with known visible or radio objects. One of these is the Crab Nebula which was first identified as an X-ray source by Bowyer, Byram, Chubb, and Friedman (1964) on the basis of a lunar occultation observation. The X-ray emission region was found to be at least 2' in diameter and centered with respect to the optical emission of the Crab by Oda, Bradt, Garmire, Spada, Sreekantan, Gursky, Giacconi, Gorenstein, and Waters (1967). The flux density (power per unit frequency) in both visible and radio exceeds that in X-rays by many orders of magnitude. The X-ray spectrum appears to obey a power law extending to at least 100 keV (Peterson, Jacobson and Pelling, 1966). The other identified X-ray source, Sco X-1, (Sandage et al. 1966) is found to be a blue, star-like object in which the flux density in the visible continuum is comparable to that found in X-rays, and which is not observed to be a radio source. The X-ray spectrum itself appears to be exponentially decreasing between about 2 and 40 keV (Peterson and Jacobson, 1966).

Regarding the radio emission from the sources examined in this survey, we find that no radio source is listed in the 4C catalogue (Pilkington and Scott, 1965) at the locations of Cyg X-1, Cyg X-2 and Cyg X-4 which puts a limit of about 2 MKS units (watts/m^2-sec (c/s)) for their radio emission at 178 mc/s. This limit may be significant in the case of Cyg X-1 which is reported by McCracken (1965) (who also noted the lack of a radio source) and by Bleeker, Burger, Deerenberg, Scheepmaker, Swanenburg, and Tanaka (1967) to have a power-law X-ray spectrum extending to at least 60 keV, similar to that of the Crab Nebula rather than that of Sco X-1. However, the radio emission from the Crab Nebula is given as 1500 MKS units in the 4C catalogue; thus, Cyg X-1 is deficient in radio by almost three orders of magnitude compared to the Crab even though the object is weaker than the Crab in X-rays by only a factor of two or three at most.

Cyg X-3 lies directly along the projection of the Cygnus spiral arm as defined by the distribution of galactic hydrogen, (Kerr and Westerhout, 1965) and almost centered within the Cygnus X radio complex; however, it does not coincide with any one of the many individual radio sources into which this region has been resolved by Downes and Rinehart, (1965). The object is within the small diameter ($\sim 1/2^{\circ}$) O association VI Cygni, (Munch and Morgan, 1953) which, if the coincidence is real, places Cyg X-3 at a distance of about 1500 pc. A possible connection between X-ray sources and O associations has been noted by O'Dell (1966). In view of the very heavy obscuration in this part of the sky (the extinction in front of one member of the VI Cygni association has been reported as being between 9 and 10m by Morgan, Johnson, and Roman (1954)) it may not be possible to attempt an optical identification. It is interesting to note in this connection that from a preliminary analysis of the data we find tentative evidence of a cutoff in the X-ray spectrum of this object at low energy that could be indicative of interstellar absorption of the X-rays.

There are a number of prominent objects in Cygnus that, a priori, were considered as possible candidates for X-ray emitters, but that we do not observe as sources. In particular, we can set an upper limit on the X-ray emission from a number of old novae which were within our field of view. Regions containing P Cyg, Q Cyg, CP Lac, V404, DI Lac and V450 were scanned with no detectable signal. To assess how meaningful our upper limits are, we have computed the expected X-ray intensity from these sources on the basis of their visual magnitude, assuming the ratio of X-ray to visible light outputs is identical to the one observed for Sco X-1. We then compare our upper limit with the expected value and we find that we observe 1/50 to 1/6 of the computed intensity. Q Cygnus, for example, which was traversed at 182 sec and at 289 sec does not appear to be an X-ray source. Its emission in X-rays is less than 1/200 of Sco X-1, while its visible light emission is about 1/10 of Sco X-1; it is thus deficient in X-rays compared to Sco X-1 by a factor of 20. The data on the old novae were taken from Payne-Gaposchkin, (1964).

However, the failure to observe X-rays from a given object as an X-ray source in the energy range 2 to 5 keV does not place a very significant limit on its X-ray emission at a slightly lower energy. If the sources are radiating by thermal bremsstrahlung, the high energy end of the spectral distribution will be of the form exp $(-h\nu/kT)$; if, as suggested by Manley (1966), the X-rays represent the synchrotron radiation of a flat distribution of electrons with a high energy cutoff, the high energy end of the spectral distribution will be of the form $(\nu_c/\nu)^{1/2}$ exp $(-\nu/\nu_c)$ where ν_c varies as the square of the electron cutoff energy. At higher photon energies, where the exponential term becomes large, a small change in the properties (e.g., temperature or cutoff energy) of the X-ray source will have a substantial effect on the X-ray emission. We can, however, conclude that the temperature of the gaseous envelopes that are frequently invoked to account for the optical continuum in old novae cannot exceed 10^7 °K.

We can summarize the results of this experiment as follows. Except for the observed X-ray sources and excluding small regions adjacent to the sources, there is no X-ray source in Cygnus as strong as 1/100 to 1/200 of Sco X-1. In particular, neither Cyg A or a number of the known old novae are observed to be X-ray sources. Furthermore, none of the X-ray sources are associated with even a very weak radio source; this includes Cyg X-3 which is in a region where the density of resolved radio sources exceeds $1/(\text{deg})^2$. Of the X-ray sources for which an optical search was made, (as discussed in the accompanying paper) one, Cyg X-1, may be obscured optically; the other, Cyg X-2, is found to be associated with a visible object that is similar to Sco X-1. Thus, it would appear that Sco X-1 is not unique and with Cyg X-2 belongs to a class of celestial objects in which the dominant radiative energy loss is in the form of X-ray, and which appear in visible light as a blue star-like object. These two X-ray sources were the only ones for which positions have been measured with sufficient accuracy to attempt a search for an optical counterpart (apart of course for the Crab Nebula) and which are not badly obscured. Thus, it must be presumed, on the basis of what we now know, that several of the other known galactic X-ray sources also belong to this same class.

We wish to acknowledge a number of illuminating discussions with Professor Bruno Rossi of MIT, Dr. Oscar Manley of AS&E, and Dr. Allan Sandage of the Mount Wilson and Palomar Observatories. The work was supported by the Office of Space Science Applications of National Aeronautics and Space Administration under Contracts NAS W-1505 and NAS W-1583. We wish also to acknowledge the cooperation and support of the staffs of the Goddard Sounding Rocket Branch and of the White Sands Missile Range.

TABLE I

	R.A. (1950)	Dec. (1950)	ℓ^{II}	b^{II}	Intensity*	Intensity**	ASE Designation	Corresponding Previous Designation
S-1	$19^h 56^m 34^s$	$35^o 6'$	71.4	3.1	.46	3.0×10^{-9}	Cyg X-1	Cyg XR-1
S-2	$21^h 42^m 48^s$	$38^o 11'$	87.4	-11.3	.45	2.9	Cyg X-2	Cyg XR-2
S-3	$20^h 30^m 52^s$	$40^o 56'$	80.0	0.7	.13	0.83	Cyg X-3	New source
S-4	$21^h 9^m 11^s$	$38^o 33'$	82.9	-6.4	.05	0.31	Cyg X-4	New source

* counts/cm^2-sec, $2 < E < 5$ keV (corrected for electronic dead time and position within the field of view).

** ergs/cm^2-sec, $2 < E < 5$ keV, assuming an exponential power spectrum $I = I_o e^{-E/kT}$, $T = 5 \times 10^7$ °K.

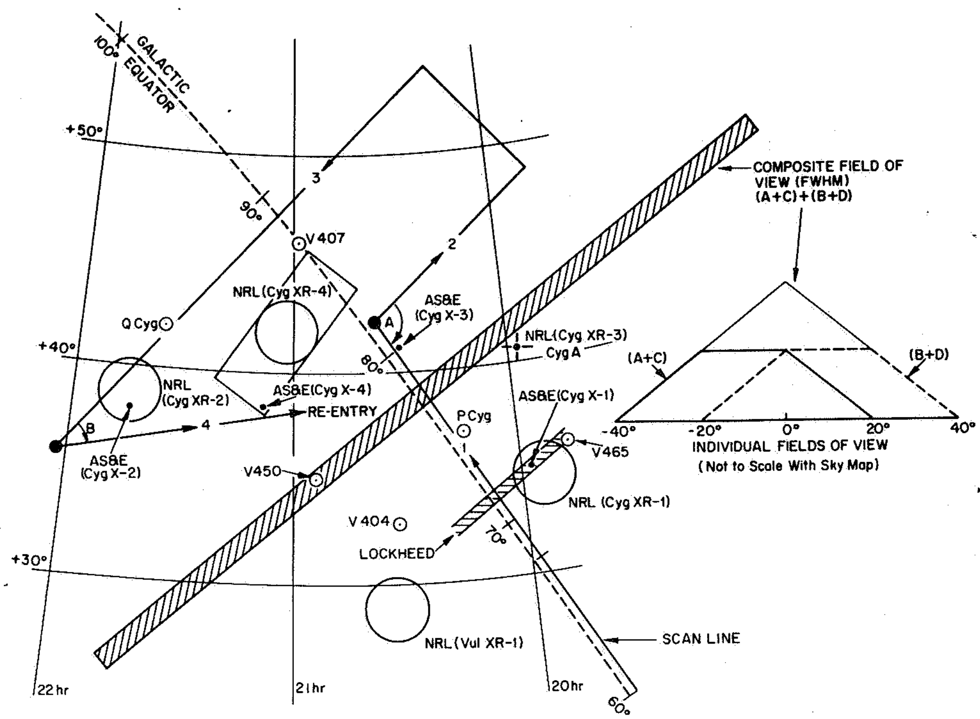

Figure 1. The lines of the center of the field of view of the X-ray detectors on the celestial sphere for the Cygnus portion of the flight are shown as a solid line with numbers and letters denoting the various maneuvers described in the text. The locations of the sources observed in this experiment (AS&E) are shown together with some previous determinations made by the NRL (Friedman, Byram and Chubb, 1967) and Lockheed (Fisher et al. 1966) groups. Several prominent novae found in the Cygnus region are shown as circles with a central dot. The insert labeled "Individual Fields of View" gives the collimator transmission plotted as a function of angle from the center of the field of view in the direction of the long dimension.

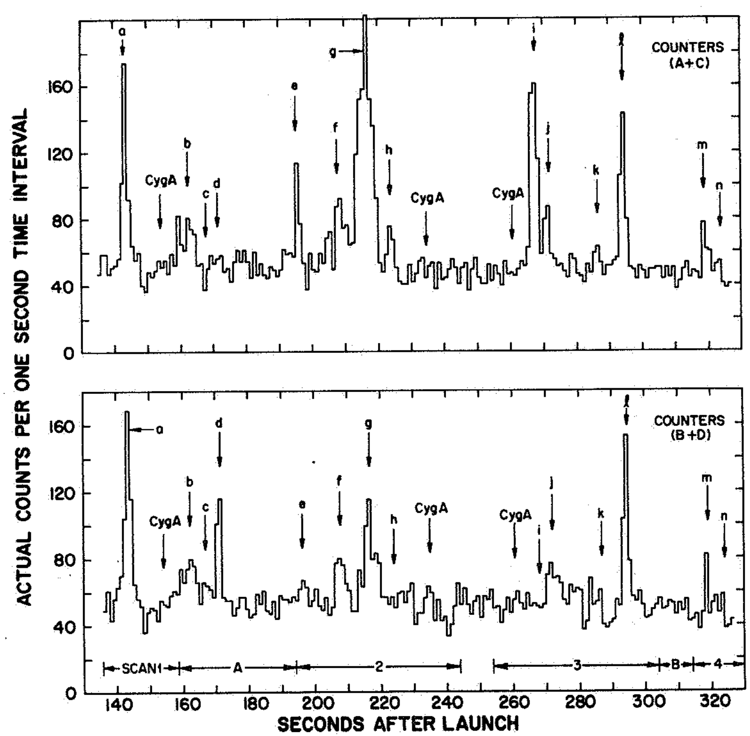

Figure 2. The histograms of actual counts per one second interval versus time for the Cygnus portion of the flight is shown for pulses falling within the photon energy interval 2 to 5 keV. The numbers and upper case letters above the time scale refer to various maneuvers described in the text. Individual source transits are observed as peaks marked by lower case letters and are discussed in the text. The width of the individual peaks reflects the angular width of the detector field of view and instantaneous rate of scan.

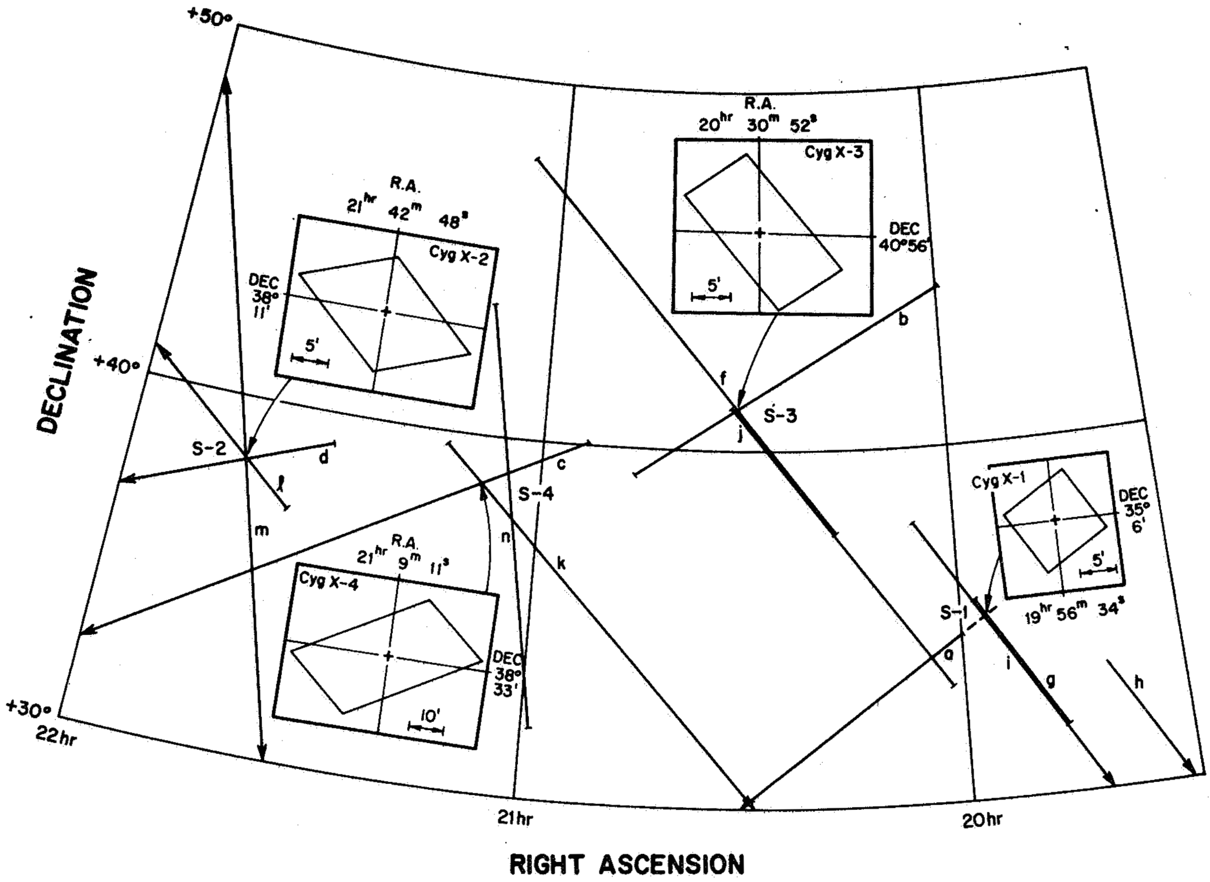

Figure 3. The lines of position as determined by each individual peak in the counting rate data is shown on the celestial sphere. The lower case letters show the correspondence to the peaks in Figure 2. The ratio of counts in the detectors (A + C) to (B + D) restricts the length of the line. As shown, the length includes $\pm$ 1σ uncertainty as determined by the counting statistics and a possible 2 degree systematic error due to differences in counter efficiency. Arrows indicate lines which continue somewhat beyond the diagram. Intersections between lines representing counting rate peaks of comparable intensity determine the location of the four sources shown. Enlargements of the intersection region show the actual location and the associated error box.

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APPENDIX B

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ASE-1610

ON THE OPTICAL SEARCH FOR THE X-RAY SOURCES Cyg X-1 and Cyg X-2

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ON THE OPTICAL SEARCH FOR THE X-RAY SOURCES Cyg X-1 and Cyg X-2

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In an attempt at identification, an optical search of the sky has been made near the new X-ray positions of Cyg X-1 and Cyg X-2 given in the previous letter (Giacconi, Gorenstein, Gursky and Waters, 1967). Anticipating the results of the rocket flight, we obtained photographic plates in August 1966 using the 48 inch Palomar Schmidt with the Haro-Luyten (1962) three-color-image technique. The plates covered an area 7° on a side and were centered near the early positions given by Bowyer, Byram, Chubb, and Friedman (1965).

The plates were inspected for objects which were peculiar in their ultraviolet intensity, adopting again the working hypothesis that the power spectrum of the source, expressed as energy per unit frequency, would be flat between the X-ray and optical region of the spectrum. The physical basis for such an extrapolation is X-ray and optical energy production by either bremsstrahlung in an optically thin plasma or by the synchrotron process for electrons possessing a flat energy distribution. This hypothesis had previously proved to be successful in the case of ScoX-1 (Sandage, Osmer, Giacconi, Gorenstein, Gursky, Waters, Bradt, Garmire, Sreekantan, Oda, Osawa, and Jugaku, 1966; Johnson and Stephenson, 1966). For that source extrapolation of the spectrum from the observed X-ray region of the 10 keV to 1 keV into the optical region (λ = 5500A) predicted V = 11.8, B-V = +0.10, U-B = -0.91 if no optical extinction were present, and indeed the optical image of ScoX-1 was seen at $\langle V \rangle \approx 12.7$, B-V $\approx$ +0.2, and U-B $\approx$ -0.8-values which are consistent with the prediction when the observed corrections for interstellar extinction and reddening of $A_V \approx 0.7$ mag, E(B-V) $\approx$ 0.23, and E(U-B) $\approx$ 0.17 are applied.

The parallel predictions for Cyg X-1 and Cyg X-2 are as follows: the X-ray intensity of both sources is about 20 times smaller than for ScoX-1 (although the sources may be variable) giving Δ mag. = 3.2 compared to the Scorpio object. Therefore, in the absence of absorption, the optical counterpart of either object should appear at V $\approx$ 15.1, B-V $\approx$ +0.1, U-B $\approx$ -0.9.

The optical absorption in front of the two sources is, however, not negligible. Cyg X-1 at $\ell^{II} = 71^{\circ}$, $b^{II} = +3^{\circ}$ is in a region of extremely heavy absorption with $A_V \geq 3$ mag. The optical image will, therefore, be faint and highly reddened with V > 18, B-V > 1.0, and U-B > -0.2. On the other hand, Cyg X-2 at $\ell^{II} = 87^{\circ}$, $b^{II} = -11^{\circ}$ is well out of the galactic plane and there is no heavy, variable absorption visible on the Palomar Sky Survey prints. The cosecant law of galactic obscuration gives $A_V \approx 1.0$ mag, E(B-V) $\approx$ 0.25, and E(U-B) $\approx$ 0.18, if we adopt Hubble's half layer absorption of 0.25 mag. Consequently, the predicted magnitude and colors for Cyg X-2 are near V = 16, B-V $\approx$ +0.4, U-B $\approx$ -0.7.

While the predictions for magnitude and color hold quite independently from the angular size of the sources, the predicted surface brightness depends directly on it. The X-ray measurements themselves do not, in the case of Cyg X-1 and Cyg X-2, furnish an upper limit to the angular size and do not exclude the possibility that the sources may appear as nebulosities sufficiently extended to be undetectable. We have in this search assumed as an additional hypothesis that the sources would appear starlike. As noted in the previous letter, this was not the case in the search for ScoX-1 where a minimum surface brightness could be computed on the basis of the X-ray data themselves.

Inspection of a one degree, square field of the three-color plate in the Cyg X-1 region revealed no peculiar ultraviolet image to an estimated limit of V $\approx$ 18 mag. Figure 1 is a reproduction of the 48 inch Schmidt Sky Survey blueprint near the source. The size of the illustrated field is 4° by 5° and is centered about $1/4^{\circ}$ north and 1° east of the X-ray position, which is indicated by a square whose dimensions are ± 10 minutes of arc on a side - the X-ray position being at the center. Our inability to detect the optical counterpart of Cyg X-1 may be due to the heavy obscuration in the field and cannot be considered as evidence against the working hypothesis. We are looking almost exactly along the inner edge of the local spiral arm (see, for example, maps in Kerr and Westerhout, 1964, Plate II and Figure 9; and Sharpless, 1964, Figure 10) - a region known to be filled with heavy dust clouds in many normal Sb and Sc galaxies.

The search was apparently more successful in the case of Cyg X-2. A region 4° on a side, centered near the X-ray position, was inspected to V $\approx$ 18 mag. Three candidate objects were found with peculiar ultraviolet properties, only one of which was near the new X-ray position, the other two being $0\overset{\circ}{.}9$ and $3\overset{\circ}{.}2$ distant. The first object is suggested as the tentative identification of Cyg X-2. It is marked in Figure 2 which is an enlargement from the Sky Survey print. The illustrated area has dimensions of 19' by 25' of arc with the X-ray position at α (1950) = $21^h\ 42^m\ 48^s$, δ(1950) = $+38^\circ\ 11'$ marked as a cross and with a portion of the error area shown as well. The optical candidate is at α (1950) = $21^h\ 42^m\ 36\overset{s}{.}91$, δ(1950) = $+38^\circ\ 5'\ 27''\!.9$ with an accuracy of about $0''\!.5$ in both coordinates. The object is well within the X-ray error box. It is the prime candidate because of its peculiar colors of B-V $\approx$ +0.4, U-B $\approx$ -0.4 with V $\approx$ 15.5 mag. - values which agree well enough with those expected on the basis of our working hypothesis. The colors and magnitude have not been measured photoelectrically but have been estimated by eye from the three-image plate using two photoelectric stars on the same plate.

From the 48 inch Palomar Schmidt plates no evidence for variability could be derived. While we have as yet no physical basis for predicting variability, we felt that this was an important phenomenological characteristic of ScoX-1 that could perhaps be common to all objects belonging to the same class and, in particular, to Cyg X-2. At the suggestion of O. Manley, the variability of this object was investigated by Usher using plates from the Harvard plate collection. Only two collections of plates, those taken with the 8 inch Ross-Lundin lens (IR series) and those taken with the 3 inch Ross-Fecker lens (RH series) had more than one plate with the object above plate limit. The RH plates were more numerous but were of poorer photometric quality and no statements on small amplitude ($\lesssim$ 1 mag) light fluctuations were possible. The IR series had better images, but only 5 plates were found which showed the candidate object.

In addition to the candidate object, twenty stars shown in Figure 3 were measured on the Harvard Askania iris photometer. The probable error of a single measurement is ±0.02 mag., but this indicates only the internal consistency of repeated measurements on a given plate and does not include systematic differences between plates. An approximate magnitude scale for the stars was established using the nearby Selected Area 41 and the Palomar Sky Survey prints. The total amplitude, Δm, of the deviations from the mean magnitude, $< m >$, are given in Table I along with the standard deviations σ for twelve stars that bracket the candidate object in brightness. The comparison stars are listed in order of decreasing brightness. While σ increases towards plate limit, we see that objects 9 and the candidate object 10 show the greatest variation with amplitudes of 1.35 and 0.90 mag. respectively. On the assumption that the other 18 stars do not vary, probable errors of ±0.15 mag. for $< m >$ can be established. The finite time resolution of the plates could increase the amplitude, if the brightness fluctuations are of the order of the exposure time (~ 60 min).

The 5 IR plates cover a time interval of from November 1939 to September 1948. Two of the plates, IR 10778 and IR 10859, were taken 19 days apart. Figure 4 presents a portion of these two plates from which the variability of objects 9 and 10 can be seen. The emulsion type is 103a-0 and the exposure times of the plates are 60 minutes and 78 minutes, respectively.

Our conclusion is that the candidate object 10 varies. Although object 9 also varies, it is not considered as a candidate because its color index is quite red, as determined by inspection of a pair of blue and yellow plates taken simultaneously with the Damon patrol camera at Harvard and it has no peculiar ultraviolet excess on the 48 inch Schmidt plates.

The a priori probability of finding an optical object within the error box for Cyg X-2 that meets the predicted magnitude and color requirements, and that appears to be variable as well, is quite small. We believe that this represents strong evidence that the candidate object may, in fact, be the X-ray source. We recognize that the area of uncertainty around Cyg X-2 contains many objects brighter than +16 mag., albeit not with the correct color. This was not the case in the ScoX-1 identification, where the optical candidate was the brightest object in the error box.

In order to make a better comparison to ScoX-1 and to gain more confidence in this identification, all efforts will be made by the Mount Wilson and Palomar group to obtain spectra and photoelectric photometry of the candidate this season when the 21^h region passes out of conjunction with the Sun. The area around Cyg X-1 will also be more carefully inspected for evidence of the X-ray source.

TABLE I

Standard deviation σ and total range of variability Δ m from 5 plates of the IR series for twelve stars in order of increasing mean magnitude.

Star	σ	Δ m	Star	σ	Δ m
21	0.11	0.25	18	0.09	0.20
20	0.07	0.15	13	0.11	0.25
8	0.07	0.15	10	0.40	0.90
17	0.13	0.30	5	0.13	0.30
9	0.60	1.35	16	0.18	0.40
11	0.07	0.15	15	0.27	0.60

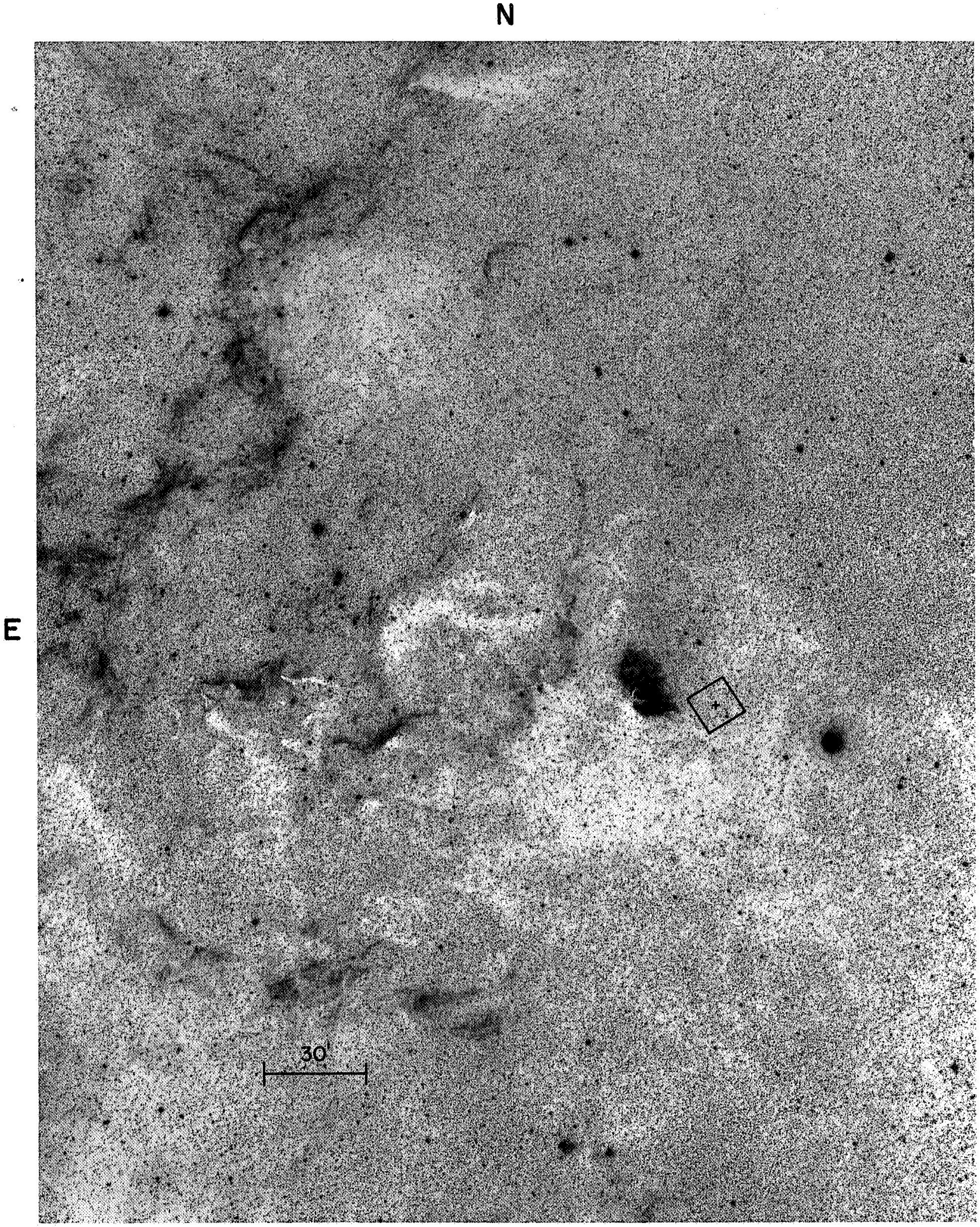

Figure 1. Reproduction of a $4^{\circ} \times 5^{\circ}$ part of the Palomar Sky Survey blue photograph near the X-ray position of Cyg X-1. The marked square is centered on the X-ray position and is the actual area of uncertainty determined for the object. Copyright National Geographic Society - Palomar Observatory Sky Survey.

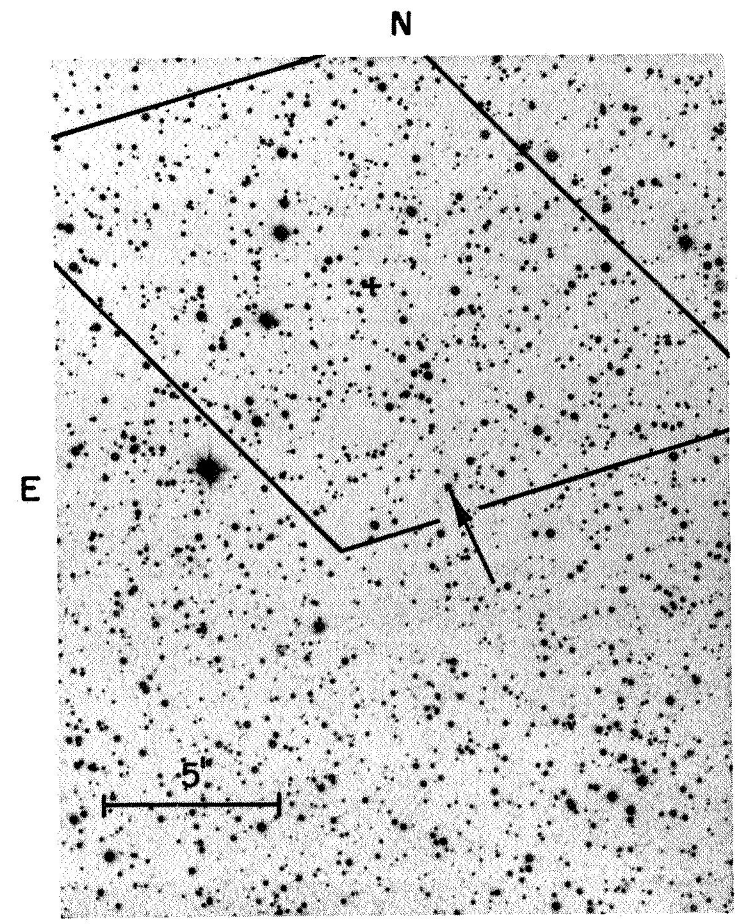

Figure 2. Enlargement of a 19' by 25' of arc position of the Sky Survey print near the position of Cyg X-2. The X-ray position is marked by a cross. The prime candidate optical object at $\alpha(1950) = 21^h\ 42^m\ 36^s.91$, $\delta(1950) = -38^\circ\ 5'\ 27''.9$ is marked by an arrow. The X-ray error box is indicated. The elongation of the optical image of the candidate object is caused by a neighboring 19th mag field star and is not due to an intrinsic structure of the candidate object itself.

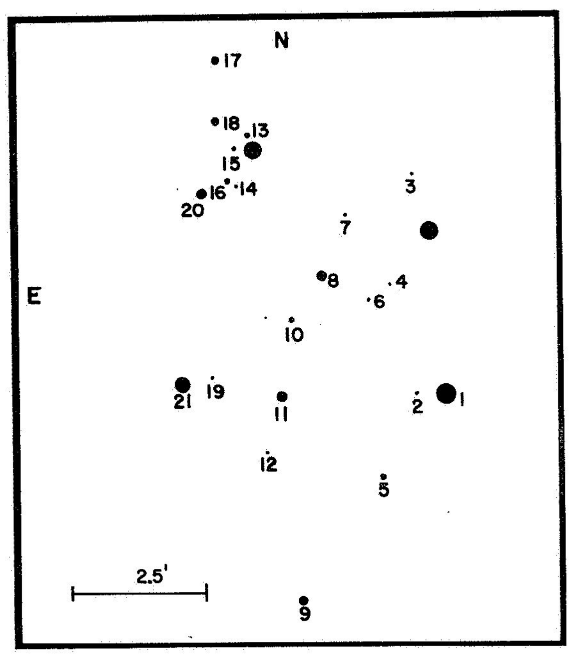

Figure 3. Finding chart for objects whose optical brightness fluctuations have been examined. Object 10 is the candidate.

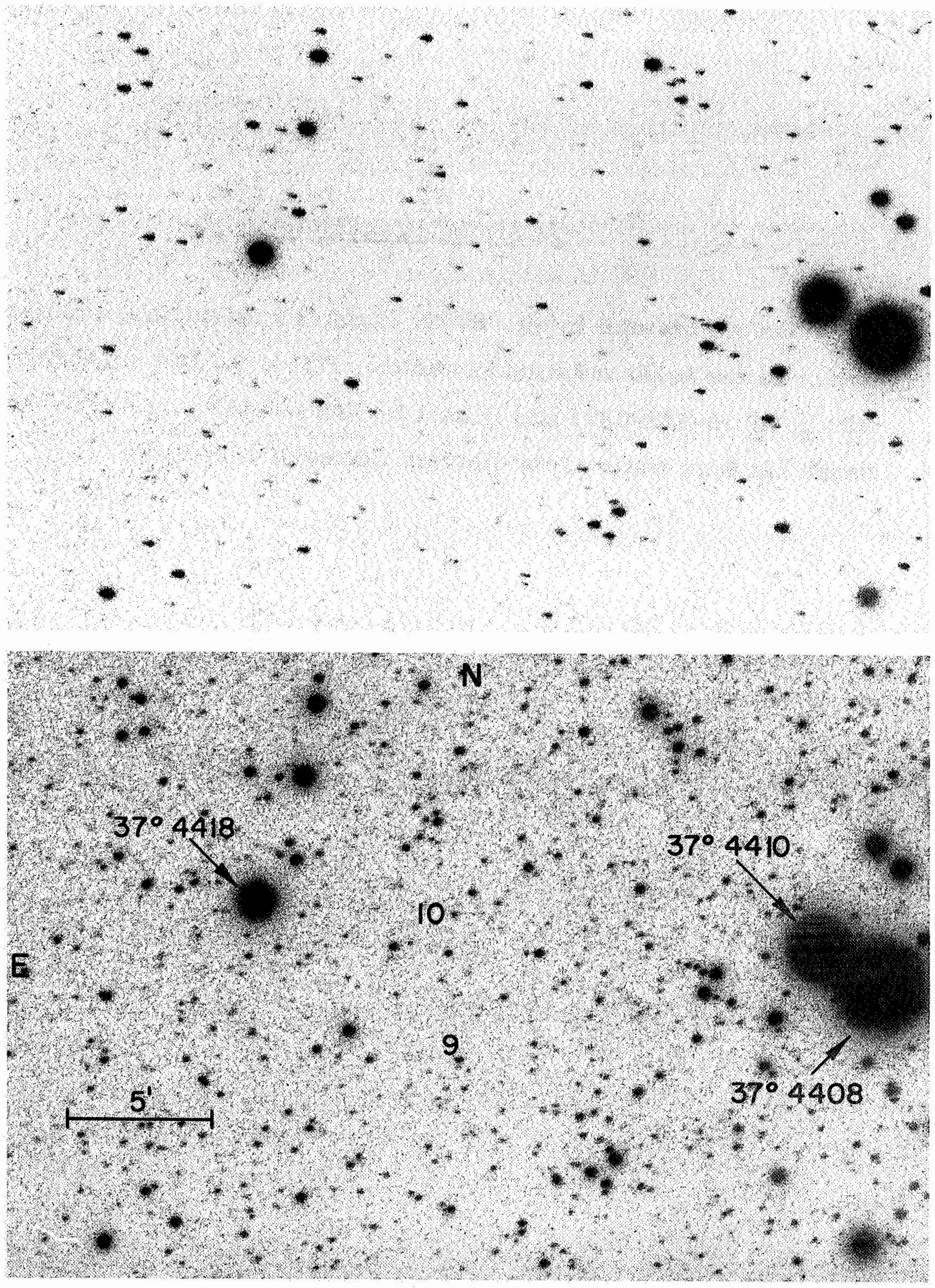

Figure 4. Portions of plates IR 10778 and IR 10859 taken on September 6-7, and September 24 - 25, 1948. The brightness fluctuations of objects 9 and 10 are clearly visible. The emulsion type is 103a-0. The exposure times are 60 min. for IR 10778 and 78 minutes for IR 10859.

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APPENDIX C

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ASE-1697

THE DIFFUSE X-RAY BACKGROUND

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ABSTRACT

The isotropic X-ray background may be interpreted by means of the superposed contributions from normal galaxies, provided that one takes into account evolutionary effects of the type suggested by the radio source counts.

THE DIFFUSE X-RAY BACKGROUND

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Beyond about 1 keV (Strom and Strom 1961, Felten and Gould 1966) our galaxy, and indeed the universe, is remarkably transparent to X-rays. Early experimental results (Gursky, Giacconi, Paolini and Rossi 1963) showed that a substantial contribution to the flux in the 1-10 keV region of the spectrum was in the form of an apparently isotropic background. The suggestion was made by Gould and Burbidge (1963) that this X-ray background may be attributable to a superposition of unresolved extragalactic sources. A recent experiment (Seward, Chodil, Mark, Swift, and Toor 1967) confirmed that the diffuse component (4-40 keV) was isotropic, to within roughly 10 percent, on scans perpendicular to and in the galactic plane. Various authors have chosen to interpret the X-ray background by means of inverse Compton radiation, which involves the scattering of an assumed spectrum of high energy electrons by thermal photons (Felten and Morrison 1966), or by the superposition of unresolved galactic sources (Oda 1965; Friedman, Byram, and Chubb 1967). We are concerned here with the latter interpretation, specifically with the statement that the superposed contributions from normal galaxies give an isotropic X-ray flux which is roughly an order of magnitude below the flux actually observed. This result is misleading in that no account is taken of cosmological effects which may entirely change the intensity and spectrum of the background radiation.

The cosmological effects that we have in mind concern the evolution of galaxies in space and/or in time. Data from radio source counts are now available to a sufficiently low flux limit to enable quantitative statements to be made concerning the luminosity function and distribution of galaxies in earlier epochs (Oort 1961; Davidson and Davies 1964; Gower 1966; Longair 1966). The observed excess of faint radio sources may be attributed, according to Longair, either to a luminosity evolution of the strong radio sources of the form

$$f(\nu) \propto (1 + z)^{3.3} \tag{1}$$

with a cut-off at $z = 3$, where $f(\nu)$ is the power of a source in ergs sec^{-1} $(c/s)^{-1}$, and z is the red-shift, or to a density evolution <u>relative to the cosmic expansion</u> of the form

$$n \propto (1 + z)^{2.7} \tag{2}$$

with a cut-off at $z = 4$. Also, Schmidt (1967) has recently presented evidence for the density evolution hypothesis (with an index of about 3) based on his determination of the optical and radio luminosity functions for quasars. Clearly, one would expect analogous evolutionary effects to occur in the X-ray region of the spectrum. However, the cut-offs calculated for the radio source counts are limited by the radio background temperature; in a similar fashion, the X-ray background will determine an effective cut-off.

In this communication, we show that if other galaxies emit X-rays at a rate comparable to that of our own galaxy, then the observed X-ray background may be attributable to a superposition of X-ray emission from normal galaxies, provided that evolutionary effects of the type believed to occur at radio or optical frequencies are taken into account. It is assumed that the strong radio sources (and possibly quasars) represent an early stage in the evolution of normal galaxies.

Consider then a model for the power emitted by our galaxy over 1-100 keV. There are believed to be two types of galactic X-ray sources, characterized by Sco X-1, with exponentially decreasing spectrum, and the Crab Nebula, with spectral index $\alpha_2 = 1.32 \pm 0.1$ over 1-100 keV (Gould 1967). Unfortunately, these are the only two sources for which adequate spectral data are available, although recent evidence indicates that Cyg X-2 may possess a spectrum similar to that of Sco X-1 (Gursky 1967), and that Cyg X-1 possesses a Crab-like power-law spectrum (Clark, Lewin, and Smith 1967). If we assume a random distribution of Sco X-1 type X-ray sources, a realistic estimate places the X-ray luminosity of our galaxy at about 10^{39} ergs/sec over 1-10 keV. For Crab-type sources, the overall X-ray luminosity is somewhat lower, at about 10^{38} ergs/sec over 1-10 keV. The flux from Sco X-1 falls off exponentially at photon energies $\gtrsim$ 10 keV (Peterson and Jacobson 1966), However, over 1-10 keV an adequate representation of Sco X-1 is a power-law spectrum with index $\alpha_1 = 1.1 \pm 0.3$ (Giacconi, Gursky, and Waters 1965). At energies $\gtrsim$ 10 keV we expect Crab-type sources to contribute to the total X-ray luminosity. Therefore, the total X-ray spectrum of our galaxy may be approximately represented by

$$f(\nu) = \begin{cases} f_1(\nu) \propto \nu^{-\alpha_1} & \text{between 1 and 10 keV} \\ f_2(\nu) \propto \nu^{-\alpha_2} & \text{between 10 and 100 keV.} \end{cases} \tag{3}$$

We shall introduce a correction factor $C(u) = u^{-m}$ [where $u = (1+z)^{-1}$], which represents an evolutionary correction, equal to unity at the present epoch ($z = 0$), and expresses the higher X-ray flux occurring in the past, because of either a luminosity evolution (1) or density evolution (2). The value of the index m is approximately 3, according to the work of Longair and Schmidt.

The total flux of radiation in ergs $\sec^{-1}$ cm^{-2} $sterad^{-1}$ observed at frequency ν_0 over a bandwidth $\Delta\nu_0$ from all galaxies in a zero-pressure Friedmann universe ($\Lambda = 0$) is given by the expression (McVittie 1965)

$$S(\nu_0) = n_g \frac{c}{4\pi H_0} \Delta\nu_0 \int_{\nu_0/\nu^*}^{1} \frac{[f(\nu_0/u)]\, C(u)\, u^{1/2}\, du}{[2q_0 + (1-2q_0)\, u]^{1/2}} .$$

Here, $n_g \simeq 2 \times 10^{-75}/cm^3$ is the present mean value of the density of galaxies (Allen 1963), $q_0 = 4\pi G \rho_0/3H_0^2$ (where ρ_0 is the mean matter density and H_0 is Hubble's constant at the present epoch) and ν^* is a cut-off frequency for $f(\nu)$ which can be estimated by means of the following considerations.

The cut-off frequency ν^* must be such as to prevent $S(\nu)$ from exceeding the observed background flux.[1] Moreover, ν^* must lie within the range

[1] We wish to emphasize that since Sco X-1 type X-ray sources do not have any significant radio emission, the cut-offs deduced by Longair for the radio source counts (in order that the extragalactic component of the radio background shall not be exceeded) are not necessarily applicable in the soft X-ray region.

over which our expression for $f(\nu)$ is valid, and account must be taken of opacity due to Thomson scattering by free electrons. Absorption of photons by pair production is appreciable only at photon energies of $\gtrsim 10^6$ MeV (Gould and Schreder 1967).

We shall evaluate $S(\nu)$ for two cosmological models, given by $q_0 = 1/2$, corresponding to the Einstein-de Sitter cosmology (or flat universe), and by $q_0 = 0$, corresponding to an open universe.

The latter case is a convenient approximation to a Friedmann universe with mean density $\rho_0 = 7 \times 10^{-31}$ gm cm^{-3} and Hubble constant $H_0 = 100$ km sec^{-1} Mpc^{-1} (for which $q_0 = 0.02$).

We first estimate the opacity of the universe due to Thomson scattering. There is a significant ($\gtrsim 10^{-6}/cm^3$) density of free electrons in intergalactic space if the intergalactic temperature $\gtrsim 10^4$ °K, as seems to be indicated by available evidence (Ginzburg and Ozernoi 1966). Optical depth unity implies a red-shift z_1 given by (Scheuer 1967) $0.046\ 2q_0 z_1^{3/2} \sim 1$, for $z_1 >> 1$. For $q_0 = 1/2$, this gives $z_1 \simeq 8$, and for $q_0 = 0.02$, we obtain $z_1 \simeq 22$. These values of z_1 represent upper limits to $\nu^* = \nu_o (1 + z_1)$ in our integration over all galaxies in the universe. Any photons emitted at a frequency $\nu_o (1 + z)^{-1}$ will not reach the observer at a time less than the Hubble time if $z > z_1$.

Carrying out the integration in equation (1) for $f(\nu)$ of the form (3), we obtain the resultant flux (for $q_o = 0$ or 1/2):

$$S(\nu_0) = n_g \frac{c}{4\pi H_0} \Delta\nu_o \; f_1(\nu_o) \left[\frac{1}{m-q_0-\alpha_1-1} \left\{ \left(\frac{\nu_1}{\nu_o}\right)^{m-q_0-\alpha_1-1} -1 \right\} + \frac{f_2(\nu_o)}{f_1(\nu_o)} \; \frac{1}{m-q_0-\alpha_2-1} \left\{ \left(\frac{\nu^*}{\nu_1}\right)^{m-q_0-\alpha_2-1} - 1 \right\} \right]$$

We see that the contribution to the flux due to the first term in the expression for $S(\nu_O)$ is approximately of spectral index m-1 for $q_0 = 0$ or m - 1.5 for $q_0 = 1/2$, while the spectral index for the second term is α_2 ($= 1.32 \pm 0.1$).

A value for the cut-off frequency ν^* may be chosen in each case to make $S(\nu_o)$ agree with the observed flux of 9.3×10^{-8} erg cm^{-2} sec^{-1} sterad^{-1} over 4-40 kev (Seward et al. 1967). The value of the corresponding red-shift z^* ($= \nu^*/\nu_o - 1$) is about 10 if the evolutionary index m is in the range 3 to 3.5 in the $q_o = 0$ model (allowing for the uncertainty in f_1 and α_1). The $q_o = 1/2$ model explains the background if m is between 3.5 and 4, and in this case $z^* \simeq 8$. The low density universe provides a reasonable fit to the data on the X-ray background over the range 1-100 keV, if we assume an evolutionary effect consistent with both radio and optical observations, and an X-ray cut-off at a red-shift of $z \sim 10$. The Crab-type sources do not make an appreciable contribution to the background unless the evolutionary index is somewhat steeper than the values we have used. The predicted spectral index is in the range 2 - 2.5, in rough agreement with the observed value of 2.3 ± 0.2 (Gould 1967). If this interpretation of the X-ray background is correct, then a low density universe is implied, with an X-ray source cut-off at $z \sim 10$. If one attempts to use a significantly lower value of the cut-off redshift, then a correspondingly larger value of m is required, which tends to steepen the resultant spectrum beyond the observed slope. This suggestion is open to observational test by means of better determinations of the spectra of the diffuse X-ray component and galactic X-ray sources, together with detection of X-ray fluxes from other spiral galaxies, such as M31. If confirmed, it should provide significant information about the manner in which galaxies evolve.

In conclusion, it seems possible that the early stages of galaxy formation may be associated with intense emission in the X-ray region. This would seem at least as plausible as the suggestion that the anomalously high intensity of the X-ray background (when evolutionary effects are neglected) is due to a large number of peculiar galaxies having X-ray luminosities in excess of our own (Oda 1965, Friedman, Byram, and Chubb 1967).

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APPENDIX D

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THE DISTRIBUTION OF GALACTIC X-RAY SOURCES FROM SCORPIO TO CYGNUS

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I. INTRODUCTION

The prevalence of X-ray sources on or near the Milky Way with the highest concentration at low galactic longitude is a well-established feature of their distribution. This clearly indicates a galactic origin for the majority of these objects of which about 30 are reported. Observation of these sources in the denser regions of the Milky Way requires high angular resolution at least in the direction along the galactic equator; a survey by Fisher, Johnson, Jordan, Meyerott and Acton (1966) of the Sagittarius-Scorpio region utilized a $1.8^{o} \times 20^{o}$ slit-shaped field of view and revealed six sources between $+20^{o} < \ell^{II} < -20^{o}$. At least four X-ray sources occur in the Cygnus region of the Milky Way (Giacconi, Gorenstein, Gursky and Waters; 1967 a, Byram, Chubb and Friedman; 1966) and perhaps five sources are in the Cepheus-Lacertus region (Friedman, Byram and Chubb; 1967). The remainder of the Milky Way has not been scanned with as high sensitivity as the above-named regions, although isolated sources are reported elsewhere.

The objective of the present survey was to establish the position of galactic sources between $\ell^{II} = -15^{o}$ and $\ell^{II} = +90^{o}$ with a higher precision and sensitivity than had been previously attained and to measure the energy spectrum of the X-rays from the stronger sources. The survey was accomplished during a rocket flight on 11 October 1966; the rocket was equipped with an attitude control system that was used to scan restricted regions of the sky. The principal elements of the instrumentation were beryllium window proportional counters with an effective area of about 800 cm^2, sensitive in the energy range 1.5 to 10 keV and collimated by slats to give a $1^\circ \times 40^\circ$ field of view at half-maximum response.

A major portion of the observational time was spent on scanning the Cygnus region and the results have been reported in an earlier paper (Giacconi, Gorenstein, Gursky and Waters; 1967a). In the present paper we report on source locations obtained when the galactic equator from $\ell^{II} = -15^\circ$ to $\ell^{II} = +70^\circ$ was scanned. Spectral data obtained throughout the flight are reported in the companion paper (Gorenstein, Giacconi and Gursky; 1967). We find 13 discrete sources in this region of which 10 are concentrated between $\ell^{II} = -15^\circ$ and $\ell^{II} = +20^\circ$. These results combined with those in Cygnus and those reported earlier in Cepheus-Lacertus by Friedman et al. (1967), show an apparent correlation with the spiral arms of the galaxy. Further considerations, based on the results of the X-ray spectra of these sources (described in the accompanying paper), allow us to construct models for the distribution of X-ray sources in the scanned region of the galaxy.

II EXPERIMENTAL DETAILS

Many of the details of the experiment are reported by Giacconi et al (1967a) and in the accompanying paper. The rocket carrier was an Aerobee 150 equipped with an attitude control system. The initial scan was along the galactic equator beginning at about $\ell^{II} = -15^\circ$. The rate of scan was 2° sec^{-1} between $\ell^{II} = -15^\circ$ and $\ell^{II} = 25^\circ$, and 4° sec^{-1} between $\ell^{II} = 25^\circ$ and $\ell^{II} = +65^\circ$. Starting at $\ell^{II} = +65^\circ$, the rocket went through a series of more complex maneuvers in order to criss-cross the Cygnus region which, as noted, was the primary objective of the flight. The precise orientation of the field of view was determined from photographs of the star field taken during the flight.

III. INTENSITY AND LOCATION OF THE X-RAY SOURCES

X-ray data obtained in the energy range 2-5 keV were used to localize sources. The detectors were divided into two groups, designated (A + C) and (B + D). Each group had an effective area of about 400 cm^2. The data in Figure 1 show the scan of the region from $\ell^{II} = -15^{\circ}$ to $\ell^{II} = +20^{\circ}$; Figure 2 shows the data taken between $\ell^{II} = +20^{\circ}$ and $\ell^{II} = +65^{\circ}$. In these two scans the long dimension of the field of view was essentially normal to the galactic equator.

We define a peak as a time-interval of the data equivalent to a 1° angle of scan (1° is the half-width of the field of view) in which the counting rate exceeds the background counting rate by three times the expected statistical fluctuation based on the number of counts occurring within that data interval. The background level was determined during those times when apparently no sources were in the field of view. On this basis, eleven peaks are found in the data of Figure 1, and two are found in Figure 2. Each of these peaks is taken to result from the transit of an X-ray source which, for convenience, we identify as S6 through S18, S1 through S5 being used to designate sources observed in the Cygnus scan and referred to by Giacconi et al (1967a). The time corresponding to the maximum of the peak, which is the same in the two groups of detectors, defines a line of position along which the source must lie. The centers of the fields of view of (A + C) and (B + D) were displaced by 20°; thus, the relative counting rates observed by the two groups of counters give crude information on the position of the source along the line. For example, S13, which is apparently caused by Sco X-1, appears in counters

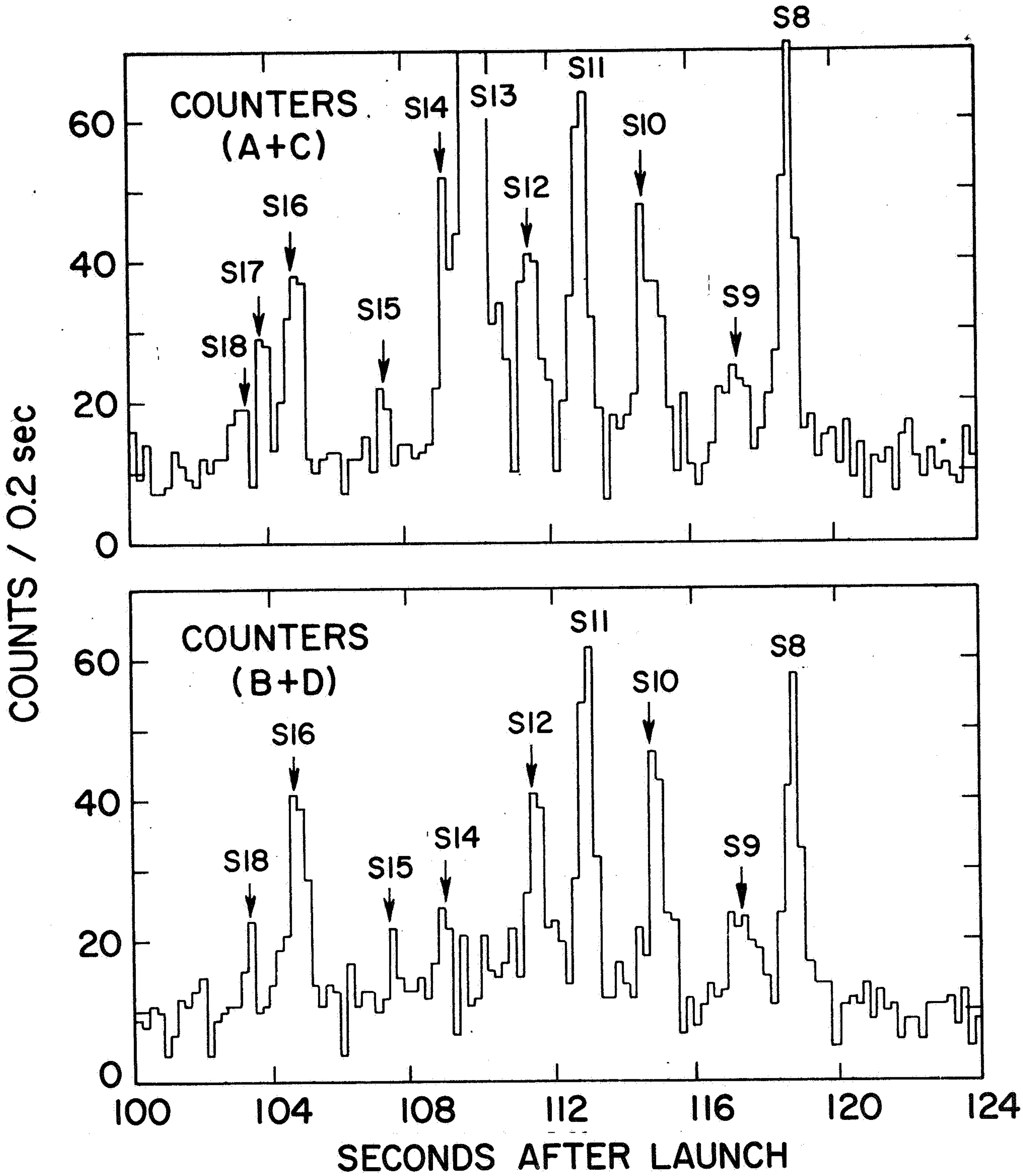

Figure 1 X-ray count histograms observed between $\ell^{II} \approx -15^{o}$ to $\ell^{II} \cong 20^{o}$. Scan rate was 2^{o} sec $^{-1}$.

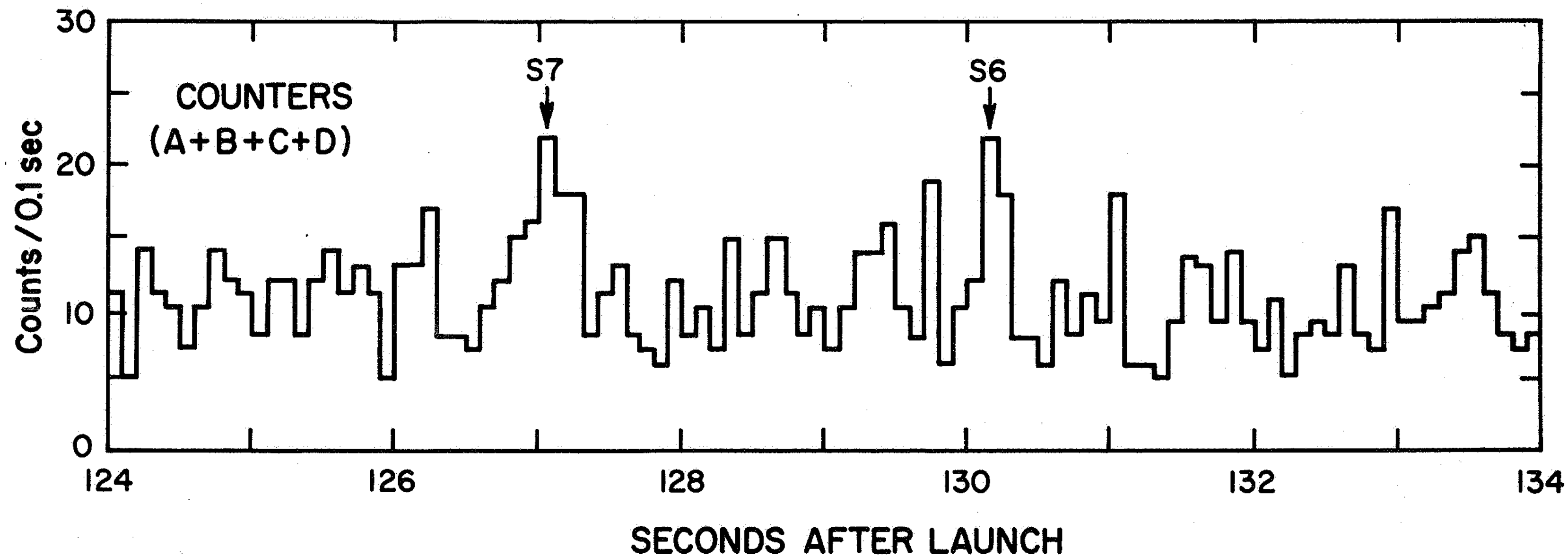

Figure 2 X-ray count histogram observed between $\ell^{II} \cong 20^{o}$ and $\ell^{II} \cong 65^{o}$. Scan rate was 4^{o} sec^{-1}. The data of the (A + C) and (B + D) detectors have been combined.

(A + C), but not at all in (B + D), which is consistent with the distance of that source from the galactic equator. Another source, S17, also appears only in (A + C) which indicates a position at least 10^{o} off the equator.

The lines of position of the X-ray sources are shown in Figure 3. Because of the orientation of the field of view at the instant of transit, these are nearly normal to the galactic equator and give the galactic longitude of the source with high precision. The position of the source along the line (galactic latitude) is given by the ratio of the counting rates in the two detectors. The length of the line is given by the statistical uncertainty in the ratio. Also plotted in Figure 3 are positions of X-ray sources at low galactic longitude reported by Clark, Garmire, Oda, Wada, Giacconi, Gursky and Waters (1964) and by Fisher et al. (1966) based on surveys of that region with instruments having comparable angular resolution to those used in the present observation. There appears to be good agreement between the various surveys. Apparent disagreements can be resolved on the basis of the somewhat poorer angular resolution of earlier surveys and differences in sensitivity, although, as discussed in the companion paper, there is some evidence for variations in intensity of these sources. Fisher et al (1966) do not report seeing S12 which may not have been resolved from the nearby and more intense S11. The remaining unreported sources may simply have been too weak to have been observed, or too close to other sources to have been resolved.

Low angular resolution surveys of the region between $+20^{o} < \ell^{II} < -20^{o}$ (c.f., Friedman et al, 1967) show considerable source confusion and cannot be directly compared to the present observations. We do show the position of Ser XR-1 as reported by Bowyer, Byram, Chubb and Friedman (1965) which is out of the region of high source density.

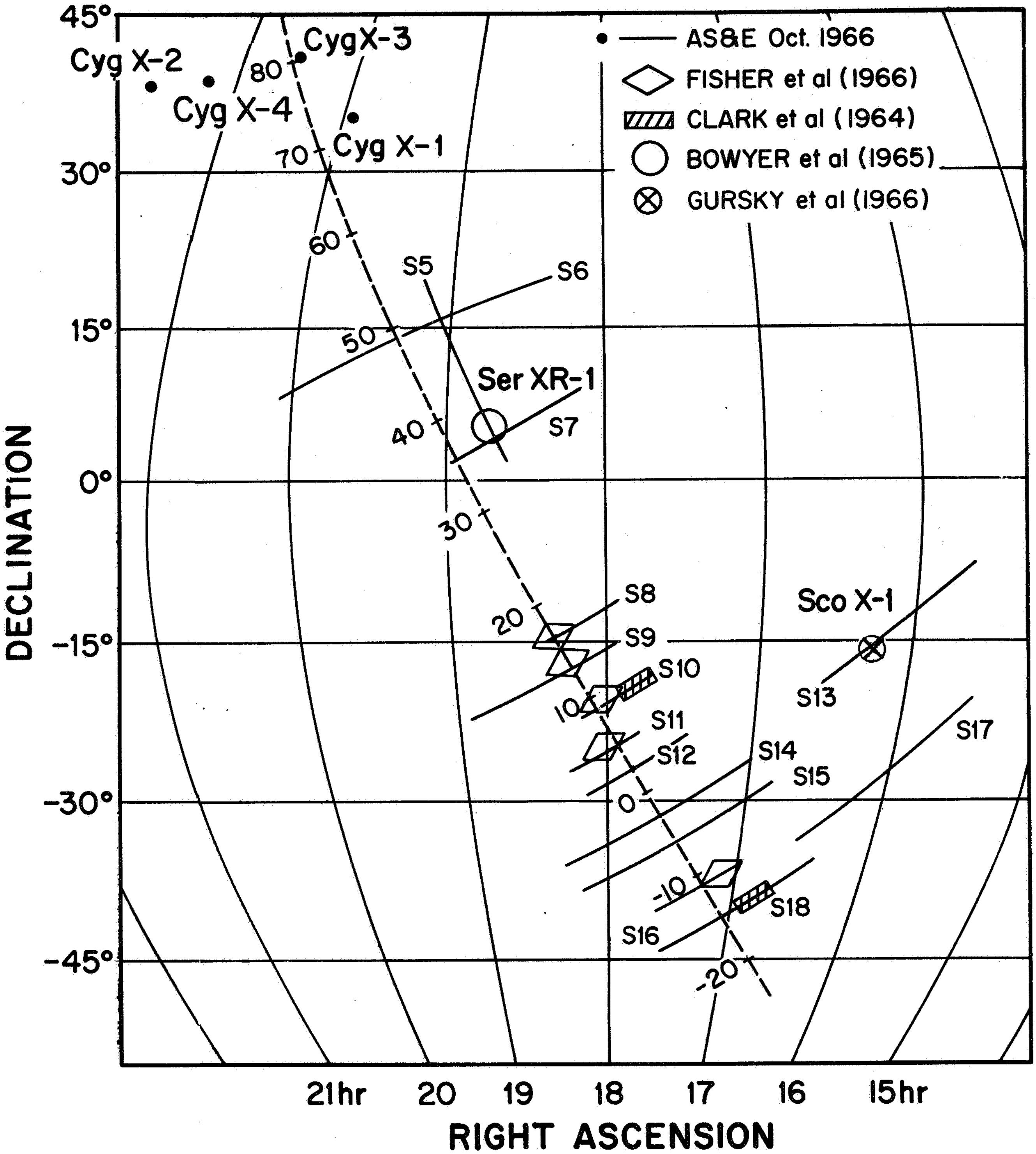

Figure 3 Position of X-ray sources observed during the present measurement compared with earlier surveys.

Although the present data contain only crude information on the galactic latitude of the X-ray sources, it is apparent from Figure 3 that we can use earlier observations to limit the range of latitude for some of the X-ray sources. Fisher et al. (1965) state that the sources at $\ell^{II} < 20^{\circ}$ are within 3° of the plane and the same conclusion was reached by Friedman et al (1967). The earlier experiment of Clark et al. (1964) shows similar dispersion in latitude for these sources. We are still left with an uncertainty of at least $\pm 3^{\circ}$ for the latitude for any given source.

A few details require further discussion. As was discussed by Giacconi et al (1967a), one of the X-ray sources observed during the scan of the Cygnus region (designated as S5) was actually located south of the Cygnus region. As shown in Figure 3, the line of position for S5 intersects both S6 and S7, and there is no basis in the counting rate data for deciding which of these two sources actually gave rise to S5. We note that S5 passes through the region of Ser XR-1 which is clearly the same source as S7.

With one exception the widths of the peaks are consistent with the angular response of the collimators, indicating an angular size of the sources of less than about $1/2^{\circ}$. The peak, S9, does appear broader than is allowed by the collimators and indicates either an emission region of about one degree extent or, what is more likely in view of the high density of sources, the presence of two sources of near equal strength within one degree of each other.

The lines of position of the X-ray sources observed in the present survey are shown more precisely in Figures 4 and 5. For the purposes of identification, we designate the source by the prefix GX followed by the galactic longitude (ℓ^{II}) of the intersection of our line of position and the galactic equator. Since our line of position is not precisely normal to the galactic equator, the true longitude is a weak function of the actual position of the X-ray source on the line.

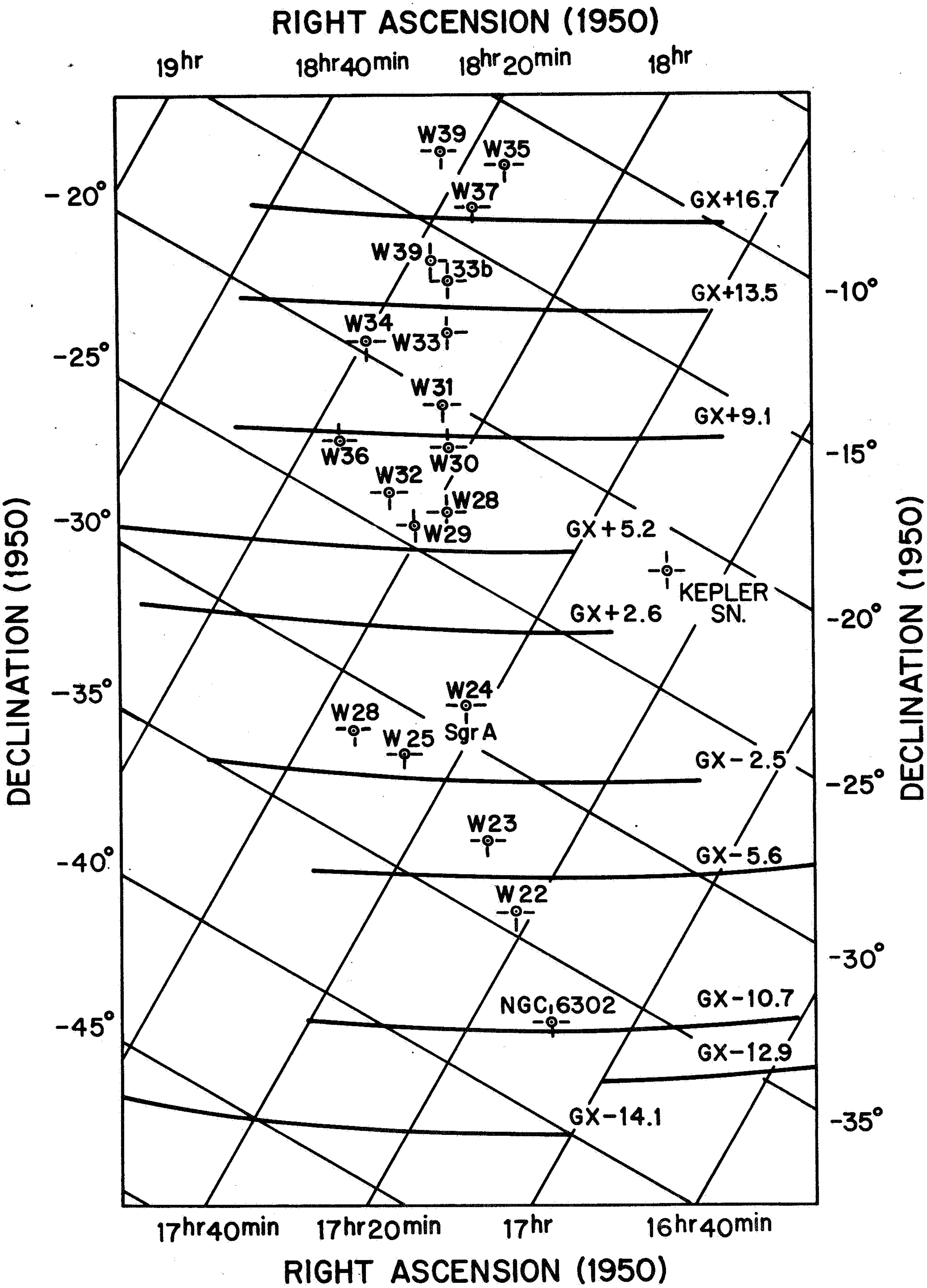

Figure 4 Lines of positions of X-ray sources between $\ell^{II} \cong -15^{\circ}$ and $\ell^{II} \cong +20^{\circ}$.

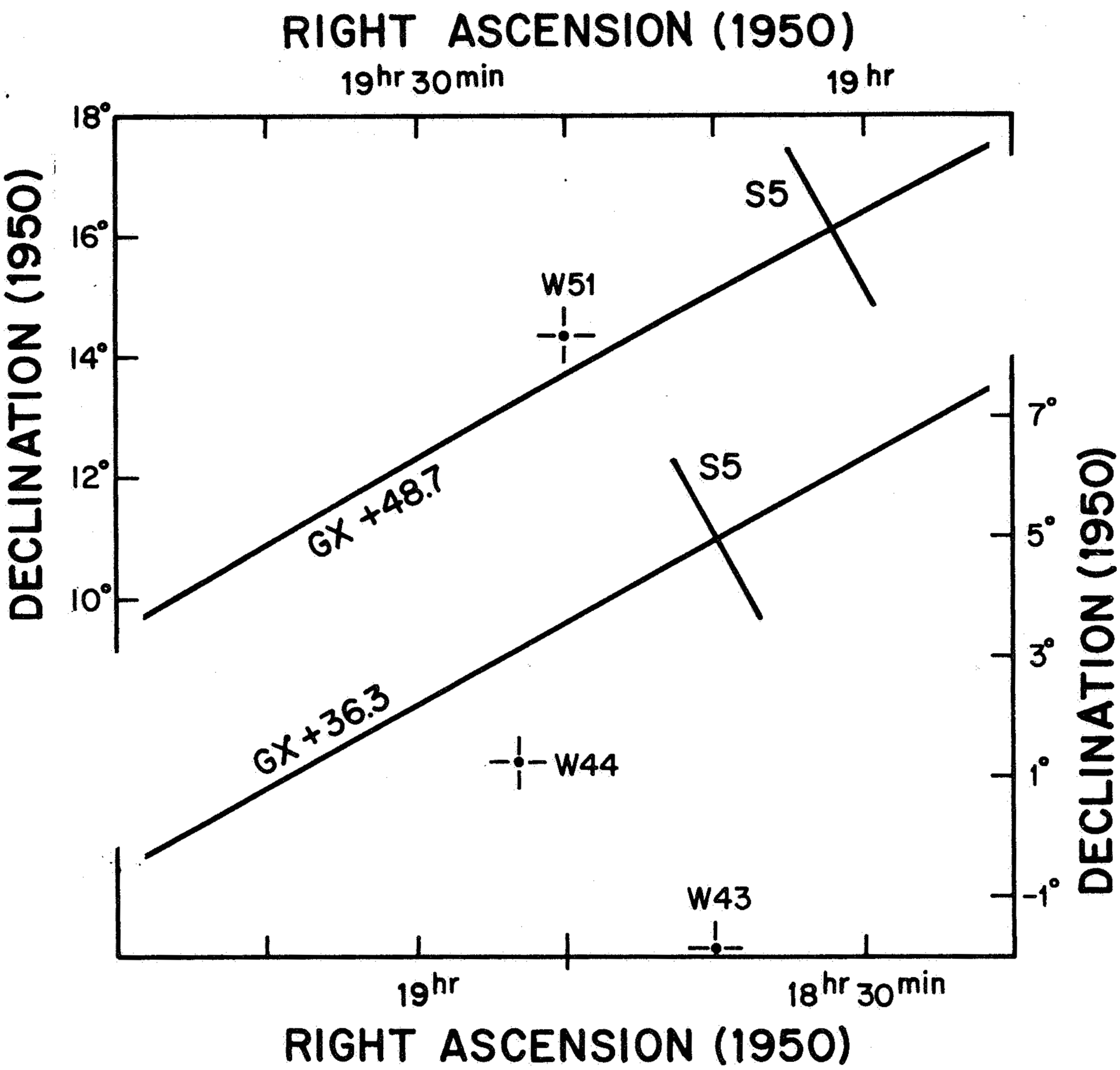

Figure 5 Lines of position of GX + 36.3 and GX + 48.7. Intersection with S5 is also indicated.

The sources are listed in Table I and include the sources in Cygnus. For the GX sources we list the uncertainty in position in the direction normal to the line of position ($\Delta \ell$) which is composed of the product of the uncertainty in determining the time of transit of the source and the rate of scan and a possible systematic error of 3', as discussed by Giacconi et al (1967a). The remaining sources of error, such as knowledge of instantaneous position of the rocket, give smaller uncertainties. Additional errors may, of course, be introduced by the possible overlap of weaker unresolved sources. The line of position we obtain for Sco X-1 (S13) comes within 8 arc minutes of the recent position reported by Gursky, Giacconi, Gorenstein, Waters, Oda, Bradt, Garmire and Sreekantan (1966) for that object. The 8 arc minutes is actually consistent with timing and position uncertainties. Since Sco X-1 is about 25° from the position of the center of the field of the detectors, a small error in rocket position produces a much larger error in source location than for the other sources.

In Figures 4 and 5, we have also plotted the positions of the radio sources given by Westerhout (1958) and several other objects. Fisher et al (1966) noted a possible correlation of one of his X-ray sources and the diffuse nebula M16 (identified as W37) and Minkowski and Johnson (1967) have noted the proximity of the peculiar nebulosity NGC 6302 and another source. Neither of these falls on one of the X-ray lines of position, and we feel that the uncertainty of positional accuracy is such that we can exclude the possibility that either of these is one of the observed X-ray sources. The galactic center ($\ell^{II} = 0$) was traversed at T = 110 sec, and there is at most a weak source (less than 10^{-2} Sco X-1) at that position. Sco X-1 blocks the galactic center region as seen in the (A + C) counters. In Figure 2 in the (B + D) counters, Sco X-1 is not apparently recorded but the counting rate is higher there than the background elsewhere. While it is possible that this increase is caused by weak, unresolved sources, we cannot exclude some residual count-rate due to Sco X-1.

	ℓ^{II}	$\Delta\ell$	b^{II}	Intensity 2 - 5 keV	Other Designation
GX - 14.1	-14.1°	±0.25°	0 ± 10°	0.11 cts/cm^2-sec	
GX - 12.9	-12.9	±0.3	> 10	0.33	
GX - 10.7	-10.1	±0.1	0 ± 5	0.90	Lockheed 3
GX - 5.6	-5.6	± 0.2	0 ± 10	0.11	
GX - 2.5	-2.5	± 0.15	0 ± 10	0.40	
Sco X-1 *	-0.9	-	23.8	19 ± 5	Sco XR-1
GX + 2.6	2.6	± 0.1	0 ± 5	0.68	
GX + 5.2	5.2	±0.1	-1 ± 4	1.24	Lockheed 4
GX + 9.1	9.1	± 0.1	2.5 ± 4	0.84	Lockheed 5
GX + 13.5	13.5	± 0.1	-4 ± 8	0.37	Lockheed 6
GX + 16.7	16.7	± 0.1	4.0 ± 3	1.25	Lockheed 7
GX + 36.3	36.3	± 0.2	9° ± 8	0.15	Ser XR-1
GX + 48.7	48.7	± 0.2	0 ± 15	0.19	
Cyg X-1	71.4	**	3.1	0.40	Cyg XR-1
Cyg X-2*	87.4	-	-11.3	0.36	Cyg XR-2
Cyg X-3	80.0	**	0.7	0.13	
Cyg X-4	82.9	**	-6.4	0.05	

*Coordinates of Optical Counterpart

**Errors are given in Giacconi et al (1967a)

POSITION AND INTENSITY OF OBSERVED X-RAY SOURCES

TABLE I

IV THE DISTRIBUTION OF THE X-RAY SOURCES

The Crab Nebula remains the only well-known object that is positively identified as an X-ray source. The recently discovered optical counterparts of Sco X-1 (Sandage, Osmer, Giacconi, Gorenstein, Gursky, Waters, Bradt, Garmire, Sreekantan, Oda, Osawa, and Jugako, 1966) and of Cyg X-2 (Giacconi, Gorenstein, Gursky, Usher, Waters, Sandage, Osmer, and Peach, 1967 b) have revealed the existence of a class of galactic objects in which X-ray emission is the dominant radiative process. There is evidence that Cas A and Cas B are weak X-ray sources (Friedman et al, 1967); however, the nature of the remaining galactic sources is not known.

Gross correlations with prominent features of the galaxy can be used to reveal the nature of the X-ray sources. Braes and Hovenier (1966) using locations given by Bowyer et al, (1965) and Clark et al, (1965), first pointed out that the X-ray sources were located close to the OB associations and that Sco X-1 and Cyg X-2 were on a line between OB associations and "runaway" stars. O'Dell (1967) attempted to demonstrate an actual coincidence between the sources listed by Fisher et al, (1966), and OB associations in the region $20^{o} < \ell^{II} < -20^{o}$. These correlations suggest that X-ray sources are young objects and that they lie in the spiral arms. Using the present data, we make similar comparisons. We first note the general distribution of certain galactic objects between $\ell^{II} = -15^{o}$ and $\ell^{II} = +90$. In Figure 6, we replot the locations of the X-ray sources reported here, along with reproductions of the radio emission obtained by Westerhout (1958), and the distributions of the optical H II regions prepared by Plaut (1965) and the old novae prepared by Sharpless (1965) plotted on the same longitude scale. The H II regions are used as indicators of spiral arms, while the old novae are considered representative of older objects that do not coincide with the spiral arms.

The distribution of the directions to the X-ray sources can be summarized as follows:

1. Most of the X-ray sources lie within several degrees of the galactic plane.

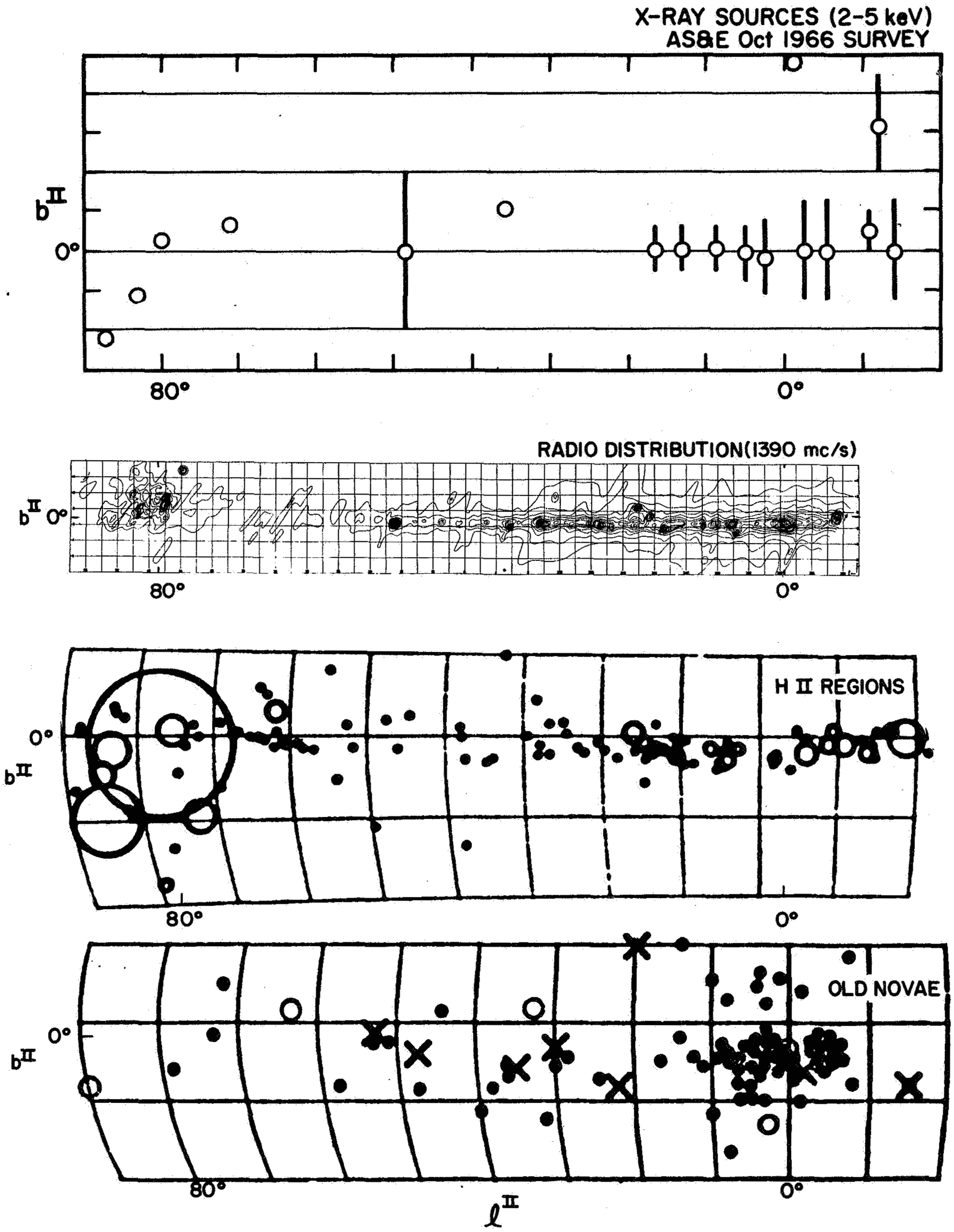

Figure 6 Comparison of the distribution of X-ray sources with known galactic objects. The radio distribution is taken from Westerhout (1959), the HII distribution is that prepared by Plaut (1965) and old novae distribution is that of Sharpless (1965). The angular scale is identical in all four plots. The X-ray positions shown are based on the present survey only.

2. The distribution in longitude is highly unsymmetrical. A large number of sources fill the Sgr-Sco region from $\ell^{II} = -15^{\circ}$ to $\ell^{II} = +17^{\circ}$; there are very few sources from 17° to 70°, and finally four sources appear in the Cygnus region.

3. The region of high source density at low galactic longitude does not extend past $\ell^{II} = 17^{\circ}$ which is in agreement with the distribution of H II regions.

4. Outside the Sgr-Sco region there is a high degree of correlation with tangential directions of the spiral arms. Based on various optical and radio studies, spiral arms are indicated as encompassing several degree regions at $\ell^{II} = 30^{\circ}$, 50°, and 80° (Kerr and Westerhout, 1965); and we observe X-ray sources at $\ell^{II} = +80.0^{\circ}$, $+48.7^{\circ}$ and $+36.3^{\circ}$, the latter two being the only sources observed between $\ell^{II} = 17^{\circ}$ and $\ell^{II} = 70^{\circ}$. The coincidence is very striking in the case of GX +80.0 (Cyg X-3) which is essentially centered within the Cyg X radio complex, and GX +48.7, for which our line of position passes close to the radio sources W51. This radio source has been resolved by Gol'nev, Lipovka, and Pariiskii, (1966) and by Mezger and Hoglud, (1967) into several distinct sources within the $+50^{\circ}$ arm at a distance of 6.5 kpc.

Points 1 and 2 suggest large distances (~ kpc) for the X-ray sources. Closer objects would be expected to show a larger dispersion in latitude and more symmetry in longitude. Points 3 and 4 support the idea that many of the X-ray sources lie within the spiral arm.

It is possible to place groups of X-ray sources within specific spiral arms, at least as a working hypothesis. However, we are faced with the difficulty that there is no commonly accepted picture of the spiral arm structure. In Figure 7 we reproduce the map of the galaxy constructed by Sharpless (1965) which is a composite of the arms as defined by optical data and by the distribution of neutral hydrogen as determined from the 21 cm radio studies.

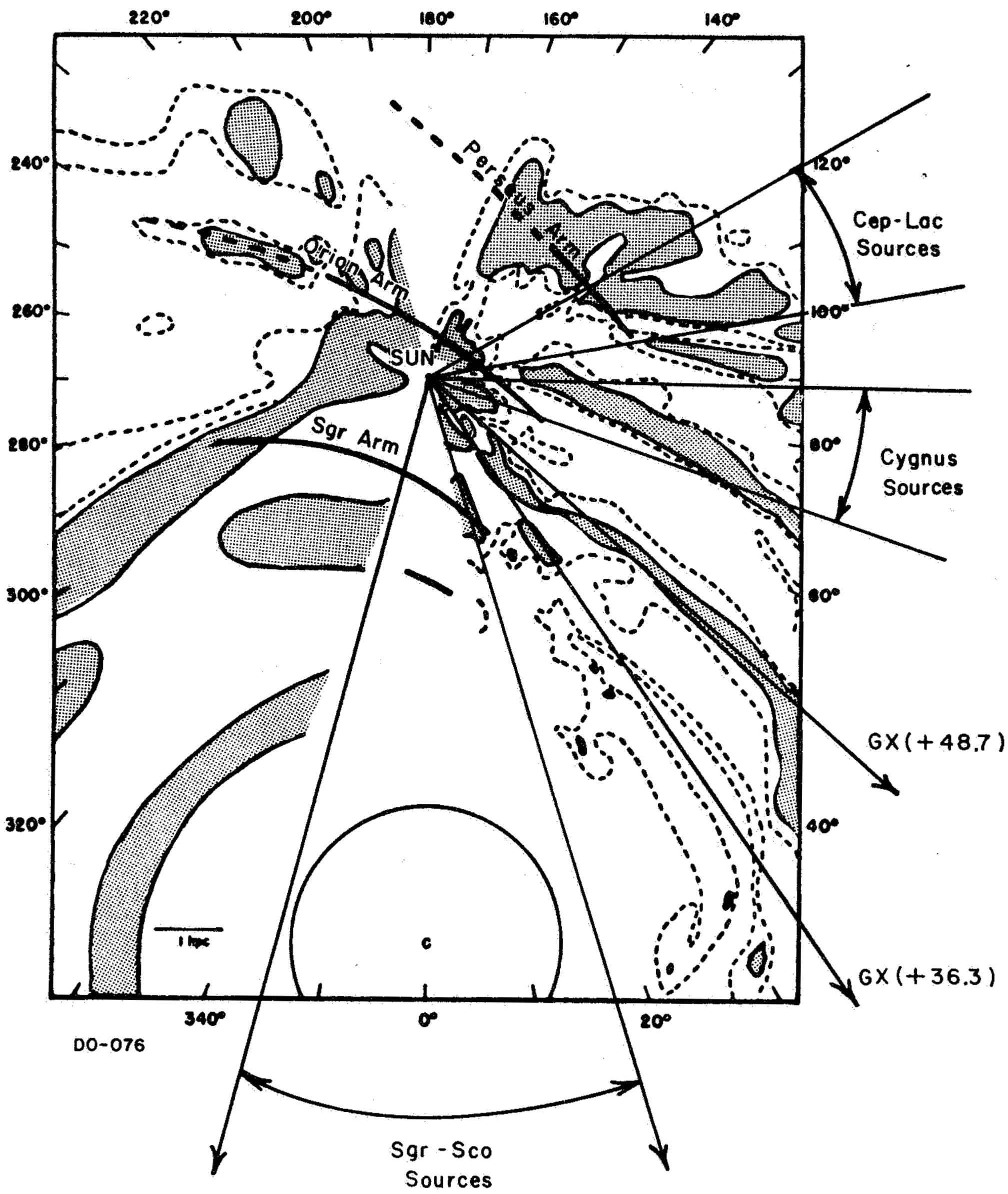

Figure 7 Direction of X-ray sources superposed on a map of the galaxy prepared by Sharpless (1965). The map shows the isodensity contours of neutral hydrogen as derived from the 21 cm radio studies and the spiral arms (shown as curved segments of solid and dashed lines) as deduced from optical data. The names used for the arms (Sgr, Orion, and Perseus) are those given by Sharpless.

On this map we superimpose the X-ray source directions. The data on the Cep-Lac sources are taken from Friedman et al, (1967).

The failure to observe sources beyond $\ell^{II} = 17^o$ in the Sgr-Sco region suggests placing that group of sources in the Sagittarius arm which, as defined by the optical data, is at a distance of 2 kpc. As seen from Table I, the Cygnus group of sources is weaker than the Sgr-Sco sources, and, as reported by Friedman et al (1967), the Cep-Lac sources are even less intense. Assuming all these sources are of comparable intrinsic luminosity, their relative intensity can be used as an indication of distance. Thus, we would prefer to place the Cep-Lac sources in the Perseus arm at a distance of 3-4 kpc rather than in the much closer Orion arm. Also, the Cygnus sources should be at greater distances than is indicated for the Orion arm as defined optically. They may be associated with the spiral arm revealed in radio that persists for about 4 kpc in the 80^o direction. In view of the differences in the radio and optical results on the arm structure, it is not possible to reach definite conclusions on the source distribution without reliable estimates of the distances to the X-ray sources. Low energy absorption data of the kind presented in the accompanying paper, in conjunction with the distribution of neutral hydrogen, can form one basis for estimating distances. It is, of course, possible that the observed absorption occurs in the immediate proximity of the different X-ray sources. However, we note the apparent correlation between absorption and galactic features - sources nearer to the galactic plane apparently exhibit a greater degree of absorption, which suggests absorption in the interstellar medium. Assuming normal abundances of the middle z element relative to hydrogen, the absorption noted for the Sgr-Sco sources requires from 1 to 3×10^{22} H atoms/cm^2 along the line-of-sight, which implies path lengths between 3 and 9 kpc. In view of the uncertainties in both the experimental data and the absorption properties of the interstellar medium, the range of uncertainty in distance must be increased even further. The largest absorption effect is observed in Cyg X-3, a source which lies along the densest portion of the neutral hydrogen along $\ell^{II} = 80^{o}$. The required line-of-sight hydrogen (3×10^{22} H atoms/cm^2) is consistent with a distance of several kpc to this object.

From the directional information and the spectral measurements we thus derive a qualitative model of the X-ray source distribution in the galaxy; namely, that the presently observed X-ray sources are located in the spiral arms. This may be indicative of their young age or of the rapidity of their evolution to the present stage. Many of the X-ray sources are several kiloparsec distance from us. This model can be used to estimate the intrinsic brightness of the X-ray sources and their abundance in the galaxy. It can also be used to compare absorption features of the interstellar material as measured in X-rays with the predictions based on optical and radio observations.

V. ACKNOWLEDGMENTS

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APPENDIX E

Preprint of a paper submitted to the
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THE SPECTRA OF SEVERAL X-RAY SOURCES IN CYGNUS AND SCORPIO

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I. INTRODUCTION

We have analyzed the spectra of several X-ray sources that were observed during a sounding rocket flight on 11 October 1966 described in the preceding paper (Gursky, Gorenstein, and Giacconi, 1967). These include the three strongest sources in Cygnus and six at low galactic longitude. The results indicate that the spectra exhibit variations in their degree of hardness and in their behavior at the low energy end. In several cases there is a deficiency of low energy photons that is consistent with either self absorption in the source or interstellar attenuation. The most notable example is the recently discovered source Cyg X-3 which is located in the Cygnus X radio complex. Neither Sco X-1 nor the two stronger X-ray sources in Cygnus exhibit this effect but it is present in several of the sources in the Sagittarius-Scorpio region.

II. EXPERIMENTAL DETAILS

The X-ray detectors consisted of eight identical proportional counters measuring 16" x 2" x 2" and containing a 1 atm mixture of 90% argon and 10% methane. The thickness of the beryllium entrance windows was about 0.003". A collimator limited the field of view to $1^{\circ} \times 40^{\circ}$, full width at half maximum. The spectral data are based on events occurring while a source was between the half transmission points of the 1° direction. Except for

Sco X-1 all these sources were observed near the center of the 40^{o} direction. Since the rate and direction of the scans were variable, the number of observed counts from each source does not necessarily correspond to its strength. The total effective area after collimation was about 800 cm^2. Several radioactive sources with energies between 1.5 keV and 22.1 keV were used in the calibration of the amplitude and resolution response of the system. The detectors proved to be fairly uniform in response over most of their length. The resolution at 5.9 keV was 21% (FWHM), and it showed the expected variation with energy. Calibration irradiations using a set of radioactive sources were made through the telemetry system several days prior to flight. Continual calibrations of the telemetry input signals were made daily up to several hours before flight by means of a pulse height analyzer. No significant drift in gain was observed. No X-ray sources were aboard during the flight itself but the expected changes in gain (on the basis of measured temperature increases during previous flights) were not significant.

The amplitude of each individual event was telemetered to ground at the time it was observed. The dead time following an event was independent of its energy. At all times during the flight (including the observation of Sco X-1) the counting rates were below the level at which spectral distortions would become significant.

III. ANALYSIS OF THE DATA

The intent of the analysis was to ascertain whether or not the fit of the observed data to an optically thin source model would be improved by the inclusion of a finite amount of low energy attenuation, and to quantitatively determine the amount needed. If the X-ray emitting region is optically thin, the spectrum will typically be monotonically decreasing except for the possible effect of spectral lines. However, the flux cannot increase indefinitely with decreasing energy. The interstellar medium must eventually become opaque to X-rays and it is possible that some of the X-ray sources are surrounded by cooler gasous envelopes that cause a significant absorption effect. Finally, it may be that the actual source region is not itself totally transparent to X-rays. Whatever the nature of the attenuation the primary absorption mechanism is photoeffect by middle and low Z elements; ignoring the effect of edge discontinuities the attenuation will vary as the minus 8/3 power of the energy.

The individual spectra were analyzed by calculating the response of the detectors to an assumed photon distribution. After correction for dead time, background, and position in the field of view, the observed histograms of counts versus energy were compared to calculated histograms covering the same energy intervals. Events were grouped in seven bins of width 1 keV centered at 1.75 to 7.75 keV plus one 2 keV bin at 9.25 keV. Various factors affecting the performance of proportional counters were included in the calculation of the expected response histograms, such as the counter window attenuation, the gas absorption probability, the escape of fluorescence radiation, the amplitude dispersion due to resolution and escape, and the finite width of each entry of the histogram. The calculated and observed histograms were compared (after normalization) and the best fit was chosen on the basis of the minimum chi square. Free parameters in the assumed spectra such as a temperature or low energy attenuation parameter were determined from the best fit.

Within the observed range of energies the statistical accuracy is not sufficient for discriminating among the various possible spectral types, i.e., exponential, power law, etc. Consequently, except for Sco X-1 and Cyg X-1, where measurements do exist over a broad range of energies, there is no basis for choosing the spectral function. The energy spectrum of Sco X-1 is best represented by the exponential function characteristic of bremsstrahlung from a thin hot gas while the spectrum of Cyg X-1 is more consistent with a power law behavior. The other sources have not yet been observed in sufficient detail at the higher energies, but there are strong indications that they are not as easily seen as Cyg X-1. In the analysis the following functions (number per unit energy) were considered:

1) $Ae^{-(Ea/E)^{8/3}} e^{-E/KT}/E$ bremsstrahlung with attenuation

2) $Ae^{-(Ea/E)^{8/3}} E^{-\lambda}/E$ power law with attenuation

3) $AE^2/(e^{-E/KT}-1.)$ black body

The first function was fitted to the data from all the sources, the second to Cyg X-1 and the third to Cyg X-3. The quantities Ea, T, and λ were left as free parameters. T and λ have their conventional interpretation. Ea is the energy at which the optical depth is unity in the absorbing region. The normalization was determined by minimizing the chi square with respect to A for each fixed Ea and T or λ. The "best fit" was the parameter set Ea and T (λ) for which the chi square was a minimum. The lack of knowledge of the true spectral function means that the temperature parameter, T, (exponent, λ) of the best fit should be interpreted merely as an index of spectral hardness rather than a true physical quantity. Furthermore, since the quantities are obtained from a two parameter analysis the magnitude of Ea is correlated with T(λ). At any point away from the absolute minimum chi square, if T (λ) is incremented positively by Δ T ($\Delta\lambda$) there is a negative (positive) increment ΔEa which leaves the chi square unchanged. Hence, it is not possible to express Ea and its uncertainty ΔEa independently of T(λ).

There are several systematic errors which must limit the sensitivity of the measurement, the most important being the characteristics of the detector window. At best as could be determined its average value was 0.003" beryllium with variations of about 10%. The actual detector wall attenuation may be somewhat greater than the value indicated by the thickness of beryllium if there is heavy metal contamination. Also, a window support structure extended into the counter interior creating a small dead region of electric field irregularities. Considering these uncertainties one must allow a systematic error that places a lower limit of about 1 keV upon the minimum value of Ea that can be determined.

IV. RESULTS

Cygnus Region

The spectral analysis of each of three X-ray sources in Cygnus is based on observations made during three separate time intervals. (See Figure 1 in Giacconi, Gorenstein, Gursky, and Waters, 1967) These intervals include scans with the 40° field of view direction both parallel and perpendicular to the galactic equator. Data from each of the three sources was obtained under conditions that are approximately equivalent with regard to total observation time, scan rate, and field of view orientation. Between the source observations there were a 5 second and a 25 second time interval in which no sources are apparent. The spectra derived from these two intervals are consistent and were taken as the background for all three sources. The observed counts and the calculated response corresponding to the best fit are shown in Figure 1 for the three sources, and the results of the fitting procedure are summarized in Table 1. The quoted errors are statistical only and are based on the sensitivity of the chi square to the parameters Ea and T. The Cygnus sources are discussed individually below.

Cyg X-1

Observations of the X-ray emission from Cyg X-1 have been made with both rocket and balloon borne instrumentation. Results cover a dynamic range of 1-80 keV. In fact, for energies greater than 40 keV it appears to be the brightest source in the sky. Spectral data at lower energies was reported by

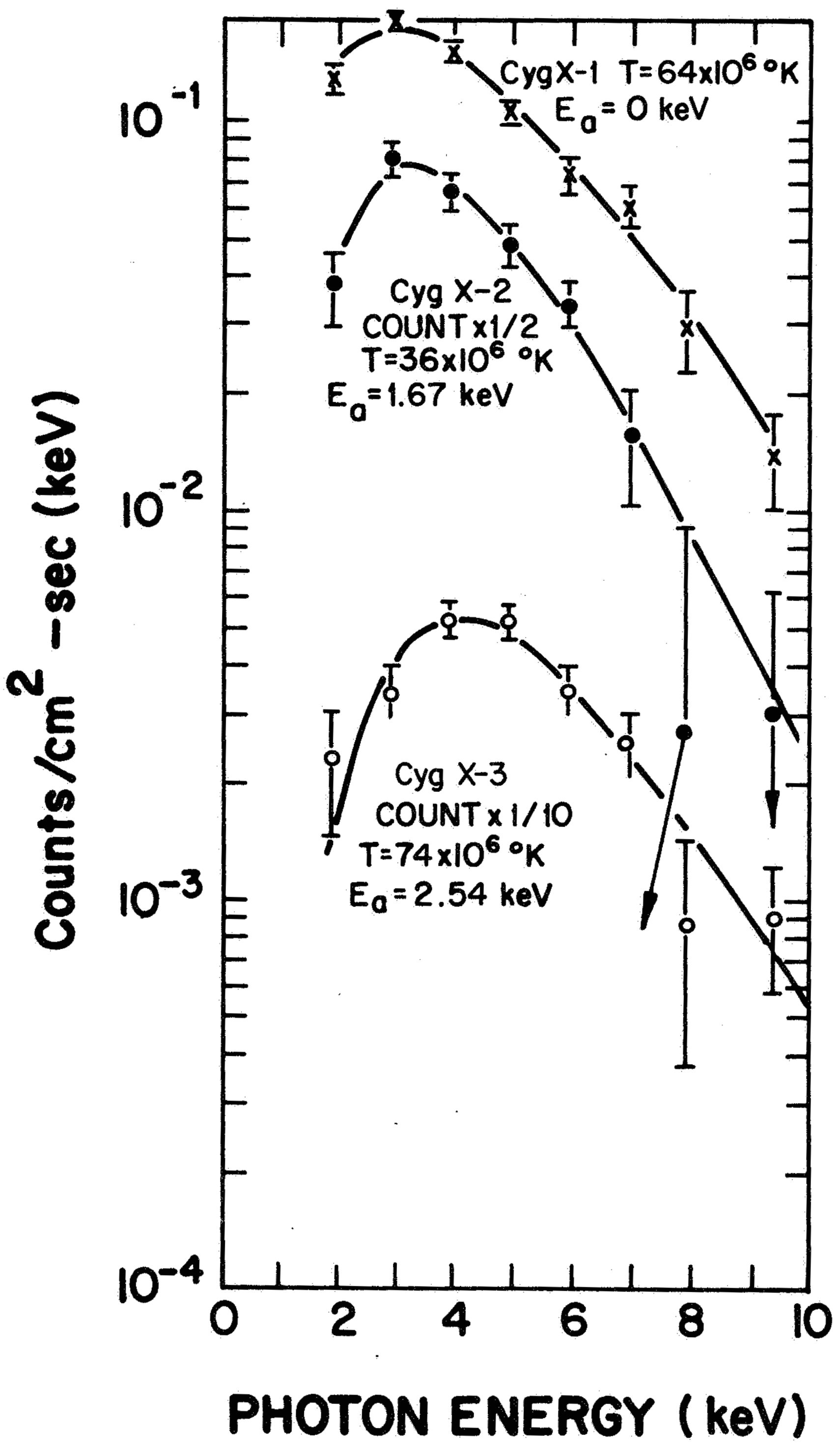

Figure 1: The histograms of counting rate versus energy are shown for three X-ray sources in Cygnus. The curves are continuous histrograms which result from the calculated response of the detectors to an assumed photon distribution, $dN/dE \sim (Ea/E)^{8/3} \exp(-E/KT)/E$. Various factors affecting the performance of proportional counters and the finite width of each energy bin are included. The quantities Ea and T were left as free parameters. The values quoted are associated with the curve representing the best fit.

TABLE I

SPECTRAL CHARACTERISTICS OF THREE SOURCES IN CYGNUS

Designation *	Fitted Spectral Type	Temperature or Exponent **	Ea ** (keV)	I (2-10 keV)+	Flux Density at 4 keV cm^{-2}-sec^{-1}
Cyg X-1	Bremsstrahlung	$64 \pm 10 \times 10^6$ °K	< 1	5.52×10^{-9}	0.57
Cyg X-1	Power Law	$0.7 \pm .1$	< 1	5.52×10^{-9}	0.57
Cyg X-2	Bremsstrahlung	$36 \pm 6 \times 10^6$ °K	$1.7^{+.2}_{-.6}$	4.08	0.49
Cyg X-3	Bremsstrahlung	74 ± 10	$2.5^{+.2}_{-.3}$	2.24	0.23
Cyg X-3	Black Body	20 ± 2	-	2.24	0.23

* Designation refers to sources described by Giacconi, Gorenstein, Gursky and Waters, 1967.

** Values giving minimum chi square. Errors are based on variation of chi square with these parameters.

\+ ergs/cm^2-sec. $2 < E$ photon < 10 keV

Grader, Hill, Seward, and Toor (1966). At the higher energies results have been reported by McCracken (1966), Bleeker, Burger, Deerenberg, Scheepmaker, Swanenburg, and Tanaka (1967), Overbeck, Womack, and Tananbaum (1967), and Clark, Lewin, and Smith (1967). Most of these other observations cannot completely exclude a contribution from Cyg X-3 which is about 10^{o} distant. The best fit of a power law spectrum to the present data gives an exponent, $\lambda = -0.7$, which is consistent with the higher energy experiments. Both the power law and the exponential function succeeded in fitting the data about equally well with no low energy attenuation required.

Cyg X-2

As seen from the best values of the fitted temperatures, the spectrum of Cyg X-2 appears to be considerably softer than that of Cyg X-1. This is consistent with most of the experiments in the higher energy range in which the latter is readily observed while the former is not. There does appear to be some low energy attenuation beyond the statistical uncertainty in the spectrum of Cyg X-2, which is seen only in the lowest energy bin.

Cyg X-3

The most interesting aspect of the spectrum of Cyg X-3 is its apparent low energy attenuation in comparison to the other two sources in Cygnus. The effect goes considerably beyond the statistical and systematic uncertainties. It is not possible to attribute this feature to instrumental effects. The effect is not confined to the first energy bin; in fact, the actual peak in the counting rate is between the third and fourth bins, at a higher energy than for any other source observed in this experiment. Three separate scans of the region, in which Cyg X-1 and Cyg X-2 are also seen, all give the same result; these include observations with the long dimension of the field of view both perpendicular and parallel to the galactic equator. Examination of additional data outside the collimator half transmission points indicates that the effect is not the result of a systematic error that is related to the difference in strength between the Cygnus sources.

It is possible to attain an equally good fit to the observed spectrum of Cyg X-3 with an attenuated bremsstrahlung spectrum and a black-body distribution having no additional low energy attenuation. With the limited wavelength range of this observation it is not possible to determine which is the more appropriate spectral type for this source. The data for Cyg X-3 and the spectral fits for both types are shown in Figure 2.

Sco X-1

Because of its high galactic latitude, Sco X-1 was observed in only half of the detectors. The large rate in combination with the telemetry requirements led to a dead time correction of a factor of three that was uncertain by 30%, but which should not have distorted the spectrum. The best fit of the observed counts to the bremsstrahlung spectrum gave a temperature of $T = 48 \pm 6 \times 10^6\ {}^{o}K$. This is consistent with the temperatures arrived at by Giacconi, Gursky, and Waters (1965), Grader et al (1966), and the higher energy measurement of Peterson and Jacobson (1966). The quality of the fit to the present data was relatively poor. Referring to the chi square the probability that the deviation is within the counting statistics is 8%. The best fit yields a low energy attenuation parameter Ea of $1.1^{+.2}_{-.7}$ keV. The quoted errors are statistical only and are based on the variation of the chi square in the two parameter fit. Considering possible systematic uncertainties we conclude that the attenuation of the spectrum of Sco X-1 is probably below the level of sensitivity of this experiment. The spectrum of Sco X-1 is shown in Figure 3A along with the spectra of two other sources observed during the same portion of the flight.

Sagittarius-Scorpio Cluster

Ten individual sources in addition to Sco X-1 were resolved between $\ell^{II} = -15^o$ and $\ell^{II} = +20$. Their names and locations are given in the preceding paper. About 6 of these gave enough counts for a spectral analysis which are shown in Figures 3A and 3B; the data were obtained during a single

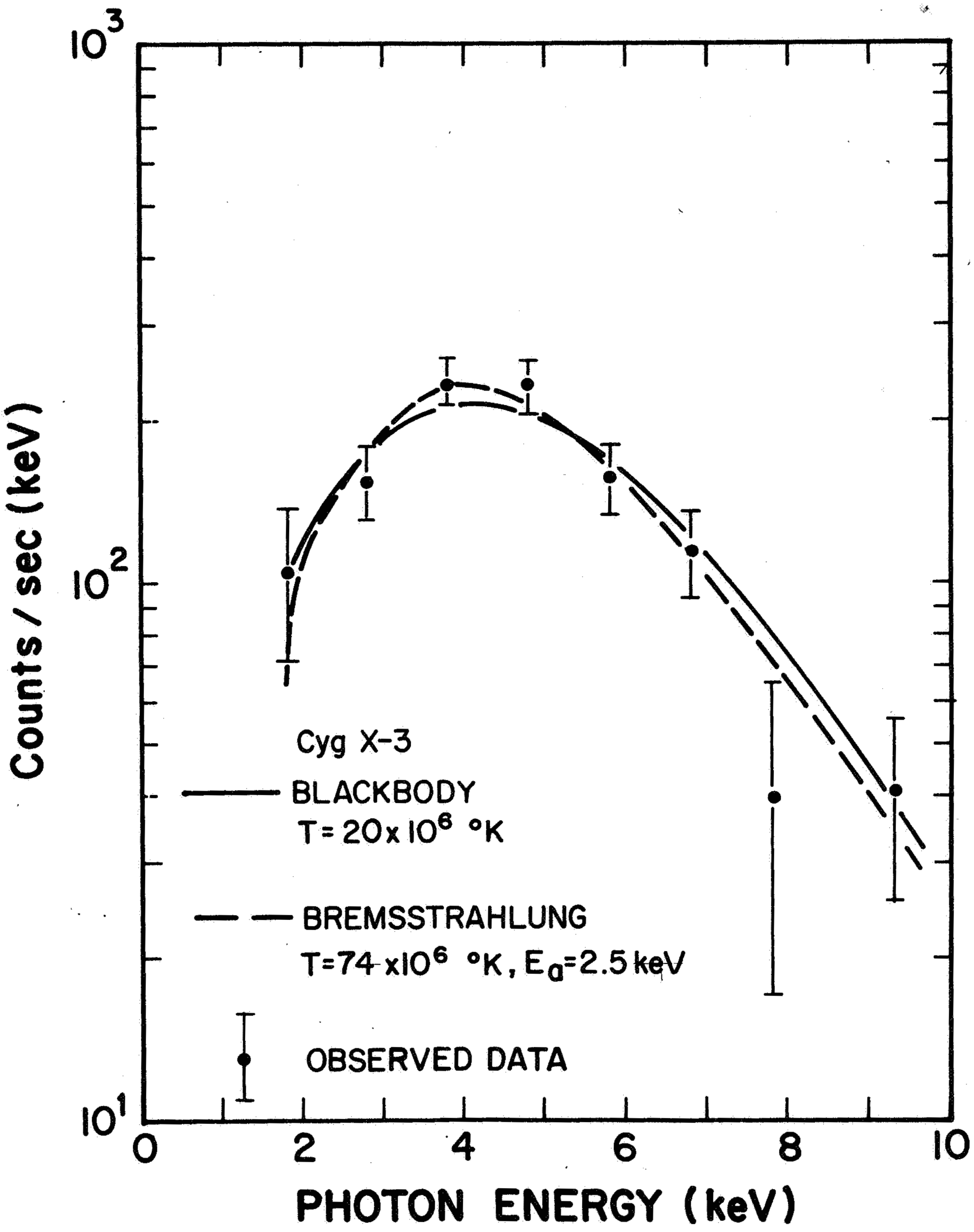

Figure 2: For the source Cyg X-3 the observed histograms of counting rate versus energy are compared to the calculated counter response to two assumed photon distributions: (1) $dN/dE \sim (Ea/E)^{8/3} \exp(-E/KT)/E$, (2) $dN/dE \sim E^2/(\exp(-E/KT)-1)$. The parameters Ea and T represent the best fit. Both spectra fit the data about equally well.

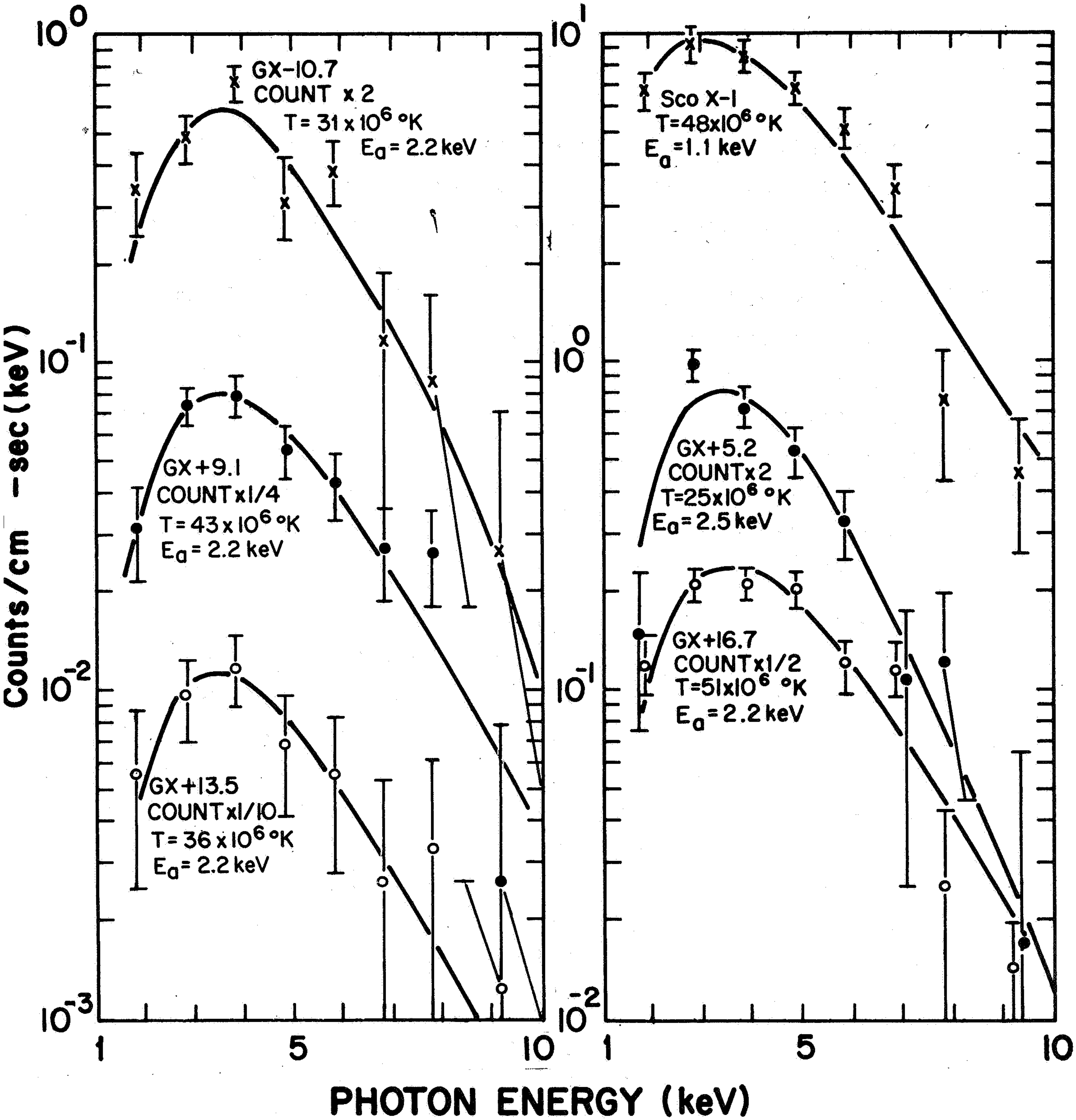

Figure 3A & 3B: The calculated counter response and the observed data are shown for six sources which lie between ℓ^{II} =-16° and +20°, including Sco X-1. Further details are given in the caption for Figure 2.

pass across the sources with the long direction of the field of view oriented normal to the galactic equator. The large source density made it difficult to evaluate the background. The counting rate in the 2-5 keV range observed during this pass is shown in Figure 4. The sources GX-10.7, +9.1, +13.5 and 16.7 are qualitatively different from Sco X-1, Cyg X-1 or Cyg X-2 in that the highest number of net counts is recorded in the bin centered at 3.75 keV. Even though the statistical precision of the individuals points is not large, the combination of the adjacent points in a given spectrum and the general appearance of the several spectra, indicates a significant low energy deficiency compared to those other three sources. The results of making spectral fits to the data points expresses this quantitatively, in that the Ea's for this group of sources are between 2 and 2.5 keV.

The exact value of Ea is difficult to determine for an individual Sgr-Sco source for several reasons. As was discussed earlier, the value Ea is dependent on the spectral function used in the fit and one's ability to determine these functions is limited by the observed energy range and counting statistics. As is apparent in Figures 1, 2, and 3, except for Sco X-1, the counting statistics are poor in the high energy bins. In this situation, not only is the analysis subject to statistical fluctuations, but also to systematic effects caused by uncertainties in the background subtraction. However, in the lower energy bins where the deficiencies are observed, the signal to background ratio and the counting statistics are still adequate to show the effect. The calculated values shown in the figures are obtained from the best fit of the assumed spectral function to the data. The combination of statistical and systematic errors places an uncertainty of about 20% in these numbers for each of the GX sources. The best values of the spectral parameters are summarized in Table II. Temperature differences among the GX sources are not significant because of the large statistical errors. However, the listed intensity and flux density are relatively insensitive to the actual fitted functions. The uncertainty in these two numbers results primarily from such factors as the efficiency and the effective area of the detectors.

TABLE II

SPECTRAL CHARACTERISTICS OF SEVERAL SOURCES IN SCORPIO AND SAGITTARIUS

Designation *	Fitted Spectral Type	Temperature **	Ea ** (keV)	I (2-10 keV)$^{+}$	Flux Density at 4 keV cm^{-2}-sec^{-1}
GX - 10.7	Bremsstrahlung plus attenuation	31 $\times 10^{6}$ °K	2.2	7.0×10^{-9}	1.37
GX - 0.9 (ScoX-1)	Bremsstrahlung plus attenuation	48 ± 6	$1.1^{+.2}_{-.7}$	246	28.3
GX + 5.2	Bremsstrahlung plus attenuation	25	2.5	9.9	0.90
GX + 9.1	Bremsstrahlung plus attenuation	43	2.2	10.8	1.28
GX + 13.5	Bremsstrahlung plus attenuation	36	2.2	3.5	0.46
GX + 16.7	Bremsstrahlung plus attenuation	50	2.2	14.1	1.66

* Designation refers to sources listed by Gursky, Gorenstein, and Giacconi, 1967 (preceding paper).

** Statistical uncertainty in temperature and attenuation is about ± 20% for these sources except as noted.

\+ $ergs/cm^2$-sec $2 < E_{photon} < 10$ keV

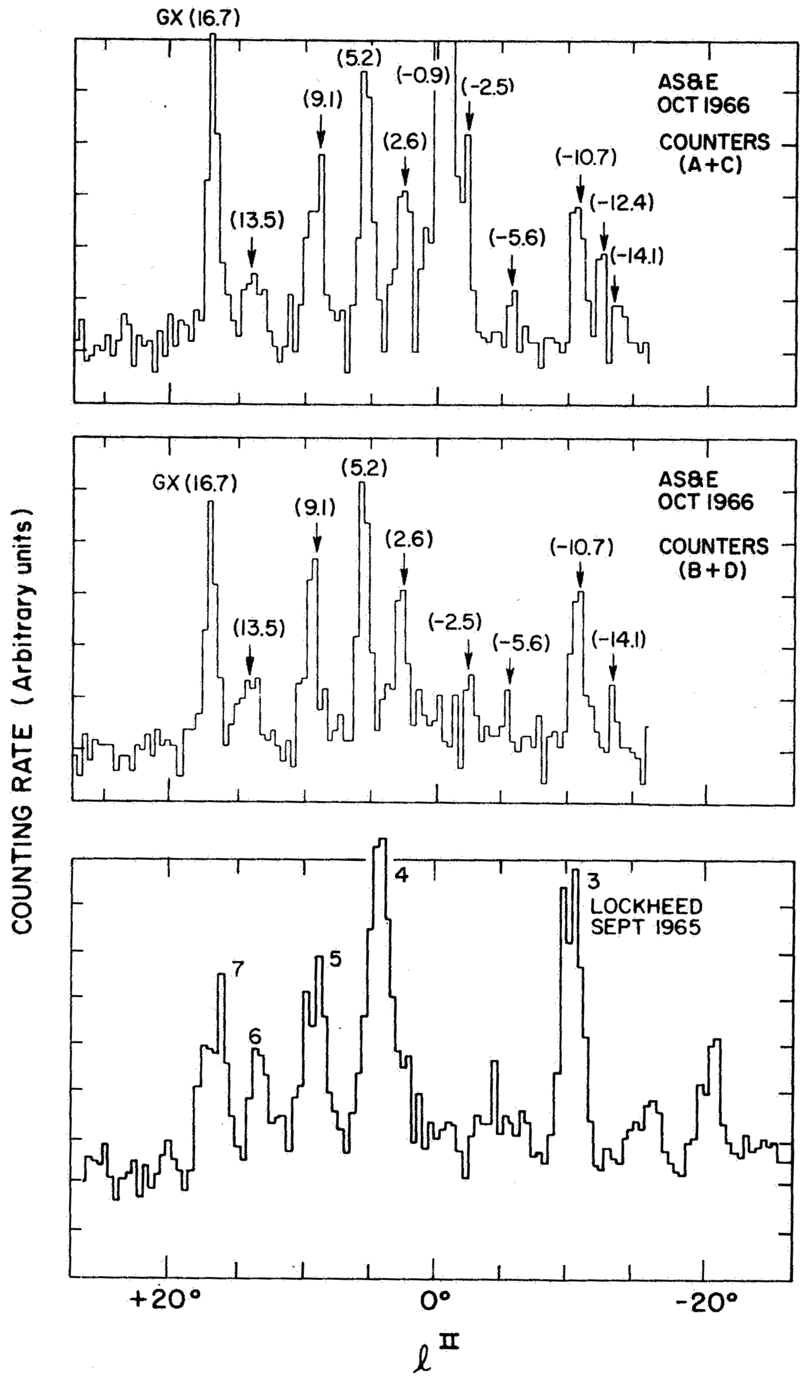

Figure 4: The Lockheed survey of 30 September 1965 (Fisher et al, 1967 a, b) and the AS&E survey on 11 October 1966 are shown on a common scale of galactic longitude. Both measurements were carried out with a field of view that was narrow in the scanning direction along the galactic equator and broad in the perpendicular direction. In the AS&E survey events were seen in two sets of counters, (A + C) and (B + D), whose field of view differed by 20° in the long dimension. Hence, Sco X-1 is seen in the (A + C) counters but not the others. Events in the figure relating to the AS&E survey are restricted to the photon energy interval 2-5 keV.

Variability

Intensity variations of Cyg X-1 and of several sources in the Sagittarius-Scorpio cluster have been reported by Friedman, Byram, and Chubb (1967). It is exceedingly difficult to make comparisons of absolute source strengths as observed by different experimental groups because of large differences in the detector spectral response, angular resolution and field of view orientation. Nevertheless, the comparison of the relative intensity distribution of a group of sources should give some indication of possible variability.

The intensity of Cyg X-1 seen in this experiment is in agreement with the observation of Grader et al (1966). We are also in agreement with the April 1965 observation by Freidman et al (1967) that Cyg X-1 and Cyg X-2 are about equal in strength although the values reported here are lower. In the case of Sco X-1 the uncertainty in the large dead time correction makes it difficult to compare its intensity with other published values.

Sources in the Sagittarius - Scorpio region were observed on 30 September 1965 by Fisher, Jordan, Meyerott, Acton, and Roethig (1966 and 1967) in a survey of the galactic equator in which the resolution (1.8^{o} FWHM) was comparable to the one in this experiment (1^{o}). Both surveys are shown in Figure 4. It appears that sources #3 and #4 of the Lockheed scan are further resolved into three and two sources respectively. A comparison of the intensity of the common sources is shown in Table III. AS&E intensities were obtained by fitting an exponential energy spectrum with $T = 5 \times 10^{7}$ ^{o}K to the observed count rate distribution between 4 and 8 keV for all the sources. For the two cases in which a Lockheed source corresponds to more than one AS&E source, the resultant intensity is corrected to the Lockheed field of view. Four out of the five sources are in relatively good agreement.

The lack of agreement between Lockheed source #3 and the three AS&E sources apparently does exceed the systematic difference between the two surveys. However, it is difficult to know precisely which source is varying. It would be interesting to compare future high resolution surveys with the present results.

TABLE III

Lockheed No.	Lockheed Intensity * (Sept. 1965)	AS&E Designation	AS&E Intensity ** (Oct. 1966)
3	1.0×10^{-8} ergs/cm^2-sec	GX-10.7, GX-12.4, GX-14.1	$.37 \pm .10$ ergs/cm^2-sec
4	1.0×10^{-8}	GX+ 5.2, GX+ 2.6	$.78 \pm .10$
5	0.7×10^{-8}	GX+ 9.1	$.62 \pm .06$
6	0.4×10^{-8}	GX+13.5	$.21 \pm .05$
7	0.6×10^{-8}	GX+16.7	$.81 \pm .06$

* From Fisher et al(1967) $4 < E < 8$ keV

** Assuming an exponential power spectrum $I = I_o e^{-E/KT}$, $T = 5 \times 10^7$ °K and fitting to observed counts between 4 and 8 keV.

DISCUSSION

The deficiency in the number of low energy photons in the spectrum of some of the sources can only be an absorption effect. The continuum spectrum of X-rays produced in optically thin sources, independent of the production mechanism, would not give the observed decrease at low energy. On the basis of the present data we cannot identify the origin of the absorption -- it could be in the interstellar material or it could be intimate to the source. Assuming the normal cosmic abundances, we can estimate the amount of material involved. The X-ray absorption coefficients of interstellar material have been calculated by Strom and Strom (1961), Hayakawa, Matsuoka, and Sugimoto (1966) and by Felten and Gould (1966). In the energy range around 1 keV, the X-rays will be absorbed primarily by middle Z elements, notably Ne and O. We will use the calculated values of Felten and Gould and give attenuation lengths in terms of H atoms/cm^2, assuming a fixed ratio of H to the middle Z elements. The attenuation observed for Cyg X-3 (Ea = 2.5 keV) requires about 3×10^{22} H atoms/cm^2 along the line-of-sight. For the Sgr-Sco sources, which show an Ea between 2 and 2.5 keV, the integrated line-of-sight density must be between about 1.5 and 3×10^{22} H atoms/cm^2.

There is at least circumstantial evidence that the absorption is taking place in interstellar matter; namely, the two sources Sco X-1 and Cyg X-2, which are furthest off the galactic plane, do not show any marked absorption effects, and the source showing the largest effect, Cyg X-3, lies along the densest portion of the Cygnus arm at $\ell^{II} = 80.0^{o}$.

On the other hand the mass required to give rise to the observed attenuation could be intimate to the source. Cameron has proposed a model of an X-ray source which is not optically thin and where the spectrum would be like that of a black body (Cameron, 1967). The Planck distribution adequately fits the data of Cyg X-3 and the Sgr-Sco sources. Still another possibility is that some of the X-ray sources are surrounded by a cooler shell which acts as an absorbing gas cloud. However, the mass requirements on the absorbing layer are modest only if the X-ray sources are small diameter objects. For example, in the case of Cyg X-3, the absorbing shell would have a thickness-density of 3×10^{22} H atoms/cm^2. If the radius of the shell is 1 A. U., then the mass of the shell would be only about $10^{-7} M_\odot$. If the shell were surrounding a large diameter X-ray object such as the Crab Nebula (about 1 pc), then the total mass required becomes greater than 10^3 solar masses, an unacceptably large figure. Hence, a measurement of the spectrum of the Crab should be decisive. The observation of an attenuation effect could only be attributed to interstellar absorption and could be used to determine the X-ray opacity of the interstellar medium.

Should interstellar attenuation not be the principal reason for the attenuation in Cygnus X-3 and the other sources, then one must consider a new class of X-ray objects in addition to the two exemplified by Sco X-1 and the Crab Nebula.

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