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CELESTIAL POSITIONS OF X-RAY SOURCES IN SAGITTARIUS*

H. Bradt, S. Naranan,† S. Rappaport, and G. Spada‡
Department of Physics and Center for Space Research,
Massachusetts Institute of Technology, Cambridge
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ABSTRACT

During a sounding rocket flight on July 7, 1967, the celestial positions of six X-ray sources in the Sagittarius region were measured with a typical precision of 20′. One of these sources, at $b^{II} = +9°$, is reported here perhaps for the first time. An upper limit of 6×10^{-10} erg cm^{-2} sec^{-1} was obtained for X-radiation (1.5–6 keV) from the Kepler supernova remnant SN 1604.

During a recent sounding rocket flight, we measured the celestial positions of six X-ray sources in the Sagittarius region with a typical precision of 20′. The existence and positions of X-ray sources at 1–10 keV in this region have been reported by several groups (Bowyer *et al.* 1965; Clark *et al.* 1965; Fisher, Johnson, Jordan, Meyerott, and Acton 1966; Fisher, Jordan, Meyerott, Acton, and Roethig 1966, 1968; Friedman, Byram, and Chubb 1967; Gursky, Gorenstein, and Giacconi 1967). The present experiment significantly reduces the uncertainty in position of some of these sources. Five of the sources lie within 2° of the galactic equator and one lies at relatively high galactic latitude ($b^{II} \simeq +9$). The latter source is reported here perhaps for the first time. The same flight yielded evidence for X-radiation from the radio galaxy M87 (Bradt *et al.* 1967).

The Aerobee rocket was launched from White Sands Missile Range at 16^h06^m sidereal time July 7, 1967. Two banks of argon-filled (3.8 mg cm^{-2}), 50-μ Be window proportional counters, each of area 350 cm^2 and each with a $2.°1 \times 20°$ (FWHM) collimator, viewed the sky through the side of the payload. The two collimators were oriented so that the long directions of the fields of view crossed one another at an angle of 60°. The rocket was controlled by an attitude-control system which caused the fields of view to scan the sky in a direction such that the two collimators would transit any given source position at the same angular distance from the center of the 20° field of view. Thus the observed intensity of any source was expected to be nearly the same in both banks of counters. Figure 1 shows the two full-width fields of view of the collimators A and B at the beginning of the scan together with the scan track of the centers of the fields of view. The light portions of the track indicate "fast" scans ($\sim 3.°5$ sec^{-1}) and the heavy portions indicate the "slow" scans ($\sim 0.°3$ sec^{-1}) across the Sagittarius region and across the bright source Sco X-1.

The rocket aspect was obtained by star photography. Each of two 16-mm cameras equipped with 25-mm, f/0.95 lenses took consecutive 1-sec exposures of the star field. The relative alignments of the optical axes of the cameras and the X-ray collimators were obtained prior to the flight from a survey, with a theodolite, of the collimators together with the photography of point light sources by the cameras. These alignments were confirmed by measurements after the flight and by the observations of Sco X-1 during the flight. The precision of the aspect determinations was about 5′.

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† On leave from the Tata Institute of Fundamental Research, Bombay, India.

‡ On leave from the Laboratorio di Astrofisica, Frascati, Italy.

The response of the two collimators to the point source Sco X-1 is presented in Figure 2 as a function of angle along the direction of scan. These data include all pulses above about 1.5 keV. The statistical errors are on the order of or smaller than the circles. The solid line is the ideal point-source response along the scan direction with the 2°.4 half-width derived from the collimator dimensions and from laboratory measurements with X-ray beams. This ideal triangular response is an excellent approximation to the actual response and will be used in the subsequent analysis. The peak intensity occurs, in each case, when the center of the field of view of the collimator was within 8′ of the blue,

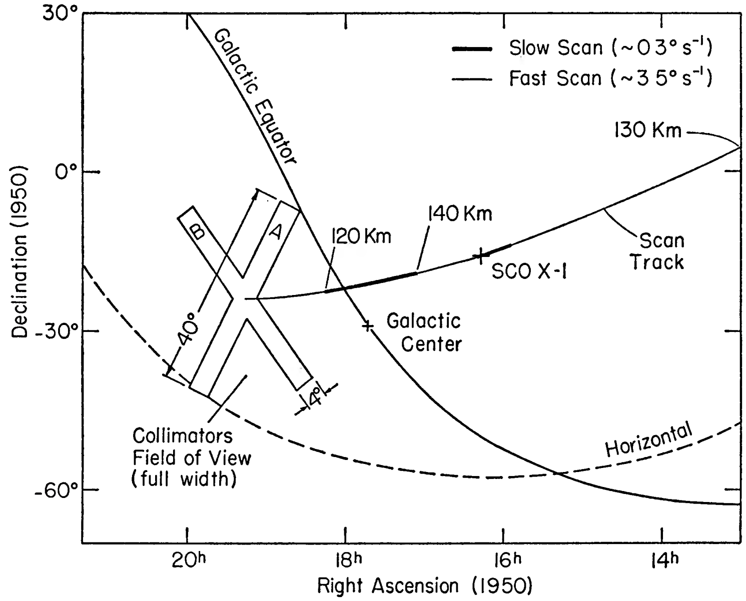

FIG. 1.—Full-width fields of view of the two collimators (*A* and *B*) at the beginning of the scan of the Sagittarius region and the scan track of the centers of the fields. Rocket altitudes are also shown.

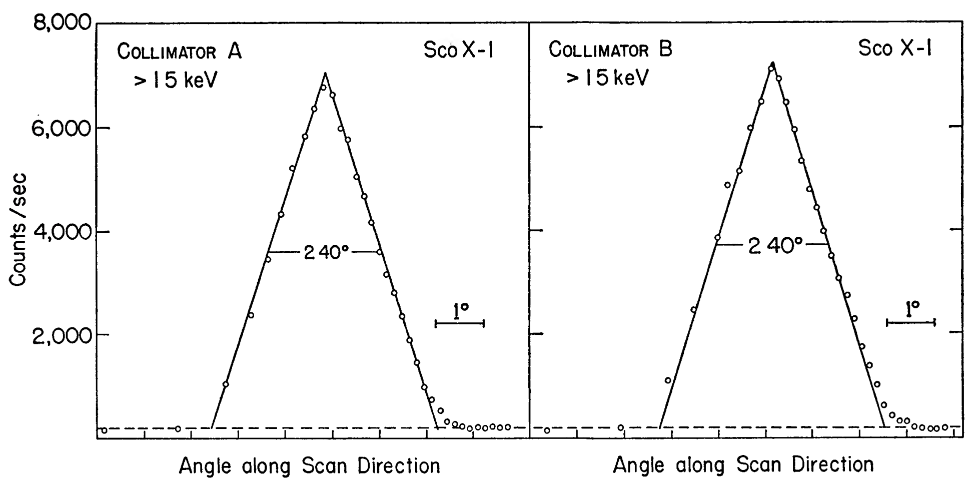

FIG. 2.—Response of each collimator to Sco X-1 for all pulse heights greater than 1 5 keV. Data are shown as circles. The solid line is the ideal point-source response with the 2°.4 half-width used in the subsequent analysis.

flickering pointlike object previously identified as Sco X-1 (Sandage *et al.* 1966). This is comparable to the combined uncertainty in the aspect and in the determinations of the peak positions. Finally, the ratio of the areas under the data peaks in Figure 2 is, as expected, near unity ($A/B = 0.97 \pm 0.01$).

The counting-rate data for the Sagittarius region are shown in Figure 3 as a function of angle along the scan direction. Only pulses in the 1.5–6 keV region are included to improve the ratio of signal to the background. A dead-time correction, at most 25 per cent in any bin, has been applied. Gursky *et al.* (1967) report that the sources in this

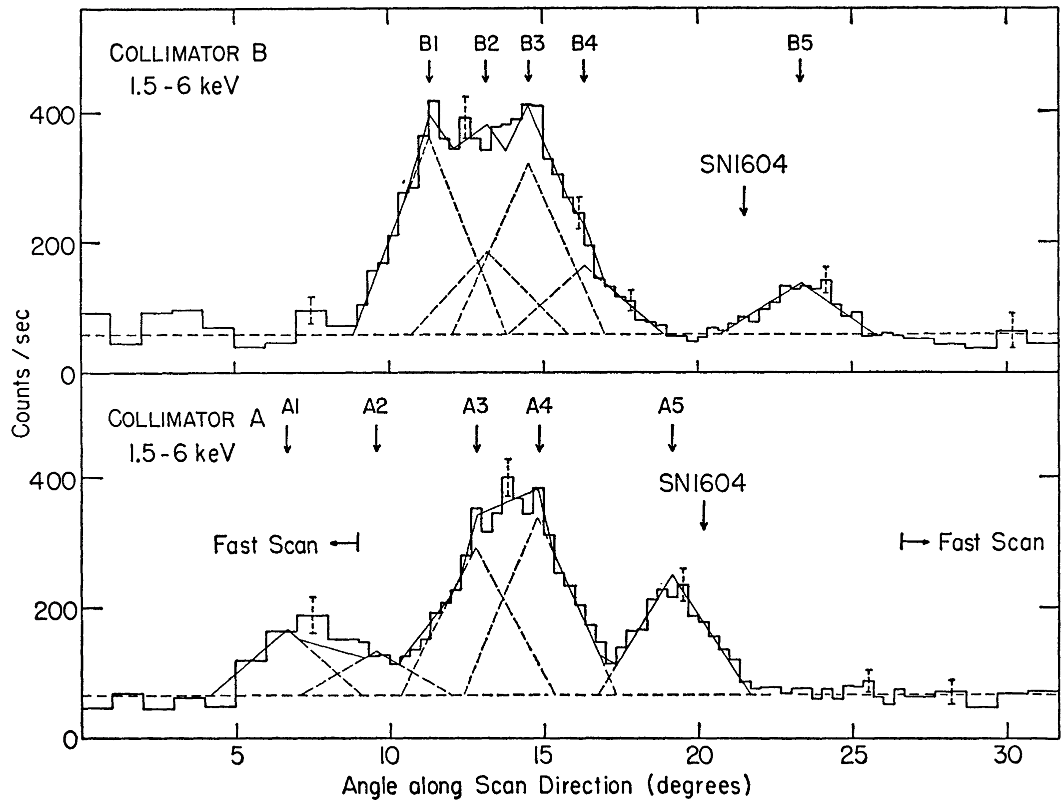

FIG. 3.—Response of each collimator to the sources in Sagittarius for pulse heights between 1.5 and 6 keV. Triangles represent the point sources which we fit to the data. The solid line is the sum of these triangles. The angular position of the Kepler supernova (SN 1604) is indicated.

region are, with one possible exception, smaller than $\frac{1}{2}^{\circ}$ in angular size. Thus we fit each set of data in Figure 3 with the minimum possible number of point sources. Each of the five postulated point sources in each set is represented by a triangle of $2^{\circ}.4$ FWHM.

The triangles were fit to the data of Figure 3 as follows. The two peaks *A5* and *B5* can each be fit with a single point source with an uncertainty in angular position of about 10′ (one standard deviation). The data peak *A3–A4* cannot be fit with a single triangle of half-width $2^{\circ}.4$. The data on the right edge of *A4* exhibit the linearity expected for a point-source response. The straight-line fit to these data and the fixed half-width of $2^{\circ}.4$ determine the height and angular position of the apex of the triangle. The difference between the data *A3–A4* and the triangle *A4* is a residue which is triangular in shape with the $2^{\circ}.4$ half-width. Thus the data indicate the existence of only one other point source, *A3*, in this complex. The uncertainties in these source positions, less than 10′, are determined by the errors in the straight-line fits to the left and right edges of this data peak. The angular position of *A1* is obtained from the leading edge of the data with good precision ($\sim 20'$). The residue of counts between the triangles *A1* and *A3* requires at least one additional source (*A2*). The complex of sources in collimator *B* cannot be understood as the sum of two intense sources but requires also the weaker sources *B2* and *B4*. The leading and falling edges of this complex directly yield the triangles *B1* and *B4*. Subtraction of these from the data then yields *B2* and *B3*. The angular position of *B2* is precise to about 20′ and the positions of *B1*, *B3*, and *B4*, quite independent of *B2*, are precise to about 10′. The error in the intensity of each of the assumed point sources is about 10 per cent except for *A2* and *B2* for which it is about 20 per cent.

The data might also include sources which are substantially less intense than the assumed point sources. Also, any of the postulated sources could be the superposition of two sources of comparable intensities which were simultaneously transited by the collimator. Prior to *A1* and *B1* and after *A5* and *B5*, there are no other peaks in the data which exceed the equivalent of a fluctuation of three standard deviations in the background. During the fast scan, this threshold amounts to a peak rate of 40 counts sec^{-1}, or a source intensity of 0.15 count cm^{-2} sec^{-1} for a source near the center of the field of view.

The data in Figure 3 exhibit no evidence for X-radiation from the Kepler supernova, SN 1604. The upper limits in intensity for this possible source, SN 1604 (1.5–6 keV), are

$$R < 0.06 \quad \text{counts cm}^{-2}\,\text{sec}^{-1}\,,$$

$$I < 6 \times 10^{-10}\ \text{erg cm}^{-2}\,\text{sec}^{-1}\,,$$

where we have assumed a number spectrum (photons keV^{-1}) proportional to E^{-2} and have taken into account our counter efficiencies to obtain the energy flux from 1.5 to 6 keV. Indications of an X-ray source near SN 1604 (Bowyer *et al.* 1965) were not confirmed during later observations (Clark *et al.* 1965; Friedman *et al.* 1967).

The location of each triangular peak in Figure 3 represents a line of position on the celestial sphere upon which an X-ray source must lie. These lines and the observed intensities are presented in Figure 4. The length of each line represents the full 40° extent of the 20° (FWHM) field of view. The intensities are the observed peak rates divided by the full 350 cm^2 detection area. Later, when we have derived the source locations relative to the center of the 20° field of view, the actual source intensities can be calculated. The collimator response in the 20° direction is nearly triangular.

The celestial positions of the individual X-ray sources must be at some of the many intersections of the *A* and *B* lines in Figure 4. Each of the sources detected in bank *A* must have been scanned by bank *B* either during the slow scan or during the preceding or following fast scans (see Fig. 4). Similarly, the sources detected in *B* must have been scanned by *A*, except that during *A*'s transit across the exceptionally bright source Sco X-1 late in the scan, one of the weaker Sagittarius sources would not have been detected. Also, the ratio of the areas under the complexes *A1–A5* and *B1–B5* in Figure 3 is close to unity and, for all pulse heights above 1.5 keV, is 0.96 ± 0.02, in agreement with the ratio for Sco X-1. This independently indicates that the *A* complex contains the same sources as the *B* complex.

The lines of position reported by the group at American Science and Engineering (AS&E) (Gursky *et al.* 1967) are shown as dashed lines in Figure 4 and are designated according to their galactic longitude (e.g., GX+16.7). The lengths of these dashed lines are derived from the relative rates of two offset $1° \times 40°$ (FWHM) collimators and thus are statistical limits to the possible source positions. The uncertainty in position in the 1° direction is typically $0\overset{\circ}{.}1 - 0\overset{\circ}{.}2$. Their intensities are for pulse heights in the 2–5 keV region in deeper proportional counters than ours. After the field-of-view corrections, the intensity of a given source in our data should be somewhat less than in their data.

To select the source positions, we look for three-way intersections of the *A*, *B*, and GX lines where the observed intensities in the *A* and *B* data are in close agreement. In the course of this analysis we are forced to assign more than one source to a given line to satisfy the data. The six source positions we obtain (*P1–P6*) are at the intersections marked by solid circles. The open circles (*P7–P10*) mark intersections for reference in the following discussion. The unmarked three-way intersections (e.g., *A3–B2*) can only be the positions of very weak sources (<0.1 count cm^{-2} sec^{-1}).

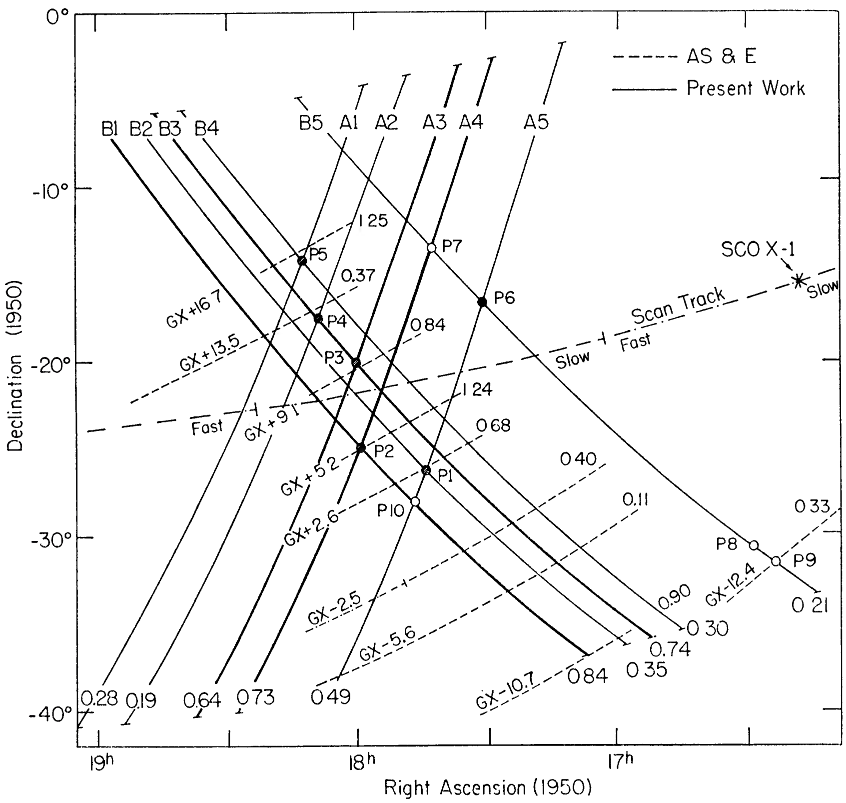

FIG. 4.—Celestial lines of position *A1–A5* and *B1–B5* derived from the data of the two collimators (*A* and *B*). The *B5* line is nearly parallel to the galactic equator at $b^{II} \cong +9°$. Dashed lines are those reported by Gursky *et al.* (1967). (The authors have informed us that the source GX−12 4 was mistakenly labeled GX−12 9 in their paper) Solid circles are the intersections where sources must lie under the assumption of no time variation in intensities between the AS&E flight (October 1966) and our flight (April 1967). Open circles mark intersections discussed in the text. The observed intensity (counts cm^{-2} sec^{-1}) is shown near each line of position. For the *A* and *B* lines this intensity is the peak rate divided by the full 350 cm^2 detection area.

The selection of the source positions was carried out in the following manner.

1. The two bright sources *A3* and *A4* can only be the bright sources *B1* and *B3*. The relative intensities of these sources suggest that *A3* is the same source as *B3* and that *A4* is *B1*. The spectral data from our experiment also suggest this association. The two intersections defined by this association, at *P2* and *P3*, are confirmed by two of the more intense AS&E sources, GX+5.2 and GX+9.1. No AS&E line of position passes through the other two intersections of these lines.

2. The source *A5* is most easily associated with *B2*, which exhibits approximately the same intensity (position *P1*). The AS&E line GX+2.6 intersects this position. There

is no other way to understand the bright source GX+2.6; that is, every other line of position from the *A* collimator intersects this AS&E line at a position which is clearly excluded by the data from the *B* collimator, and vice versa.

3. Similarly, the intensities of *A1* and *B4* suggest that they represent the same source at position *P5*. This choice is confirmed by GX+16.7 which can be understood in no other way.

4. The only three-way intersections which include *A2* are those with *B3* and *B4*. In each case, the *B* line would then represent two sources. The choice of *B4* would throw into serious disagreement the *A* and *B* intensities of the source at *P5*. For the choice of *B3*, the source at *P4* would be much weaker than that at *P3*, and our previous conclusions would not be affected. Thus we adopt the *B3* intersection at *P4* as the source position.

5. The four possible source positions for *B5* are *P6* through *P9*, each on an AS&E line or its extrapolation. *P6* and *P7* are at precise three-way intersections. *P8* and *P9* are in the region where the *A* collimator is blanked or partially blanked by Sco X-1. *P6* is the most probable position for this source. This choice implies that *A5* and GX+9.1 each represent two sources. The AS&E data peak for GX+9.1 is bright and might well contain a weaker second source, whereas the appearance of the data peak *A5* in Figure 3 as a single source is more coincidental. The density of sources and the resolution of the collimator yield a 5–10 per cent probability for this latter coincidence. The choice of *P7* places two sources on GX+13.5 with a total intensity, after the field-of-view corrections, well in excess of the reported intensity for GX+13.5. In general, we find our corrected intensities to be about $\frac{2}{3}$ those of AS&E. This choice (*P7*) also brings about a discrepancy in the *A* and *B* intensities of the source at *P2*. This can be corrected only by placing another source on line *B1* at *P10* in the region where the AS&E counters were partially blanked by Sco X-1. *P8* is improbable because the AS&E results as well as those of Fisher *et al.* (1968) and Friedman *et al.* (1967) indicate that the GX−10.7 source is nearer $\alpha = 17$ hours. *P9* is consistent with the position of GX−12.4 but, after a large field-of-view correction, is grossly inconsistent with its intensity. The data of collimator *A* just after the Sco X-1 transit further suggest that the *B5* source is not at *P9*. Also, the evidence cited above that the *A1–A5* complex (Fig. 3) contains the same sources as *B1–B5* argues against *P8* and *P9*. Thus we adopt the position *P6* for the *B5* source.

6. GX−2.5 was scanned to the west of the *A5* intersection by collimator *A* with a threshold less than the intensity expected from the AS&E data. No source was detected. The fast scan by collimator *B* to the east of this point did not have a sufficiently low threshold. Thus the source GX−2.5 must lie east of 17^h50^m on the reported line of position (*dot-dash line* in Fig. 4) if its intensity had not diminished since the AS&E flight in October 1966.

7. We find no other evidence in our data for the sources GX−5.6, GX−10.7, and GX−12.4. Their reported intensities and their positions far from the centers of the 20° fields of view could easily render them undetectable in our experiment.

The six X-ray sources at *P1* through *P6* are designated according to their galactic coordinates, i.e., GX $l^{II}b^{II}$ in Figure 5 and Table 1. The most probable positions of the sources are obtained from a consideration of both the Massachusetts Institute of Technology (MIT) and the AS&E lines of position together with the quoted uncertainties. These modified positions are again designated *P1–P6*. The error circle around each of these positions (Fig. 5) encompasses the region within which the source lies, according to our estimates, with a probability of over 90 per cent (two standard deviations). The precision of several of the three-way intersections in Figure 5 ($\sim$15′) substantiates our estimates of the errors incurred in fitting the triangular responses to the data of Figure 3. The rather large error circle for GX13+1 takes into account the possibility that the AS&E data peak represents an extended source (Gursky *et al.* 1967) and that our peak *A2* (Fig. 3) has a large positional error ($\sim$40′) and could also represent an extended

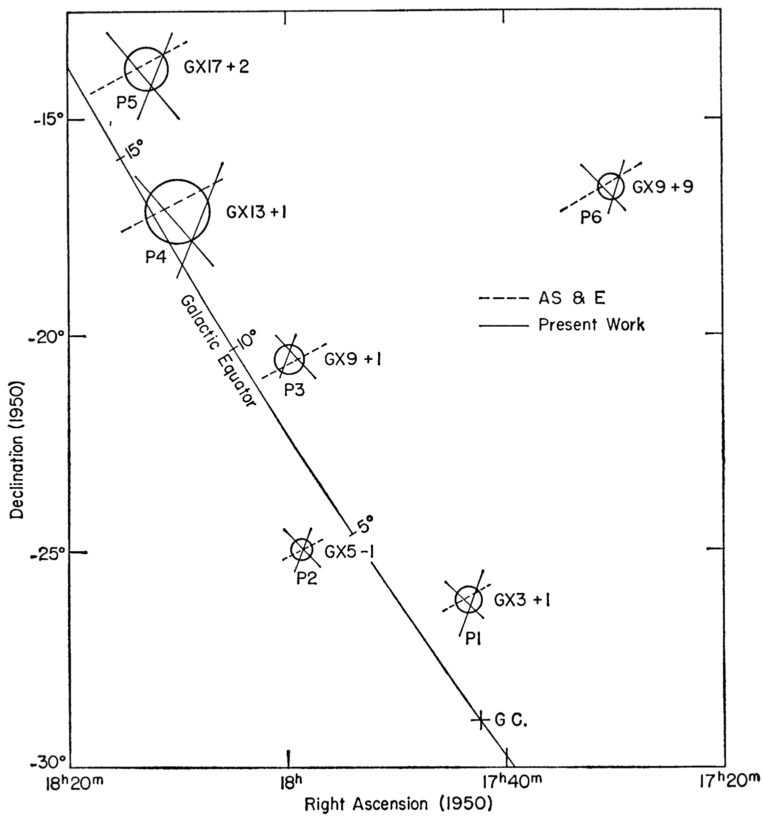

FIG. 5.—The expanded celestial plot showing the quality of the three-way intersections, the error circles, and the relation of the X-ray source positions to the galactic equator. Each error circle incloses a region wherein the sources should lie with a confidence of approximately 90 per cent (2 standard deviations). The smallest error circle is 0°5 in diameter.

TABLE 1

POSITIONS AND INTENSITIES OF OBSERVED X-RAY SOURCES

Source	Position	Coordinates (1950)				Error Circle* (radius)	Intensity†	Other Designation		
		α	δ	l^{II}	b^{II}			AS&E‡	Lockheed§	NRL‖
GX3+1	*P1*	17^h43^m4	−26°08′	2°5	+1°3	17′	0 40	GX+2 6	L14	Sgr XR-1?
GX5−1	*P2*	17 58 6	−25 00	5 2	−1 1	15	95	GX+5 2	L17	. . . .
GX9+1.	*P3*	17 59 7	−20 32	9 2	+1 0	20	60	GX+9.1	L18, L19	Sgr XR-3
GX13+1	*P4*	18 10 0	−17 08	13 3	+0 7	45	25	GX+13.5	L20	Sgr XR-2
GX17+2	*P5*	18 12 7	−13 48	16 6	+1 5	30	55	GX+16.7	L21	Ser XR-2
GX9+9	*P6*	17 30 2	−16 36	8 9	+8 8	18	0 25			

* The source lies within the error circle with a probability of ~90 per cent

† Counts cm^{-2} sec^{-1} in the energy interval 1 5–6 keV The error in intensity is ~10 per cent, except in the case of GX3+1 and GX13+1 for which it is ~20 per cent An intensity of 1 count cm^{-2} sec^{-1} corresponds to an energy flux of 10^{-8} erg cm^{-2} sec^{-1}

‡ Gursky, Gorenstein, and Giacconi (1967).

§ Fisher, Jordan, Meyerott, Acton, and Roethig (1968).

‖ Friedman, Byram, and Chubb (1967).

source region. The intensities of the six sources after correction for the field of view are also presented in Table 1.

We call particular attention to the source GX9+9. It was derived from the data peak *B5* in Figure 3 which yielded a line of position nearly parallel to the galactic equator at $b^{\mathrm{II}} \simeq +9°$. Its spectrum in our data differs significantly from the typical spectrum of the other sources in this region. In the absence of time variations in the intensity of this source, between the AS&E and MIT flights (October 1966—July 1967), we must place the source at *P6*. On the other hand, if we do allow for variations, we cannot exclude with certainty the positions (1950) *P7* ($\alpha = 17^{\mathrm{h}}42^{\mathrm{m}}.3$, $\delta = -13°18'$) or,

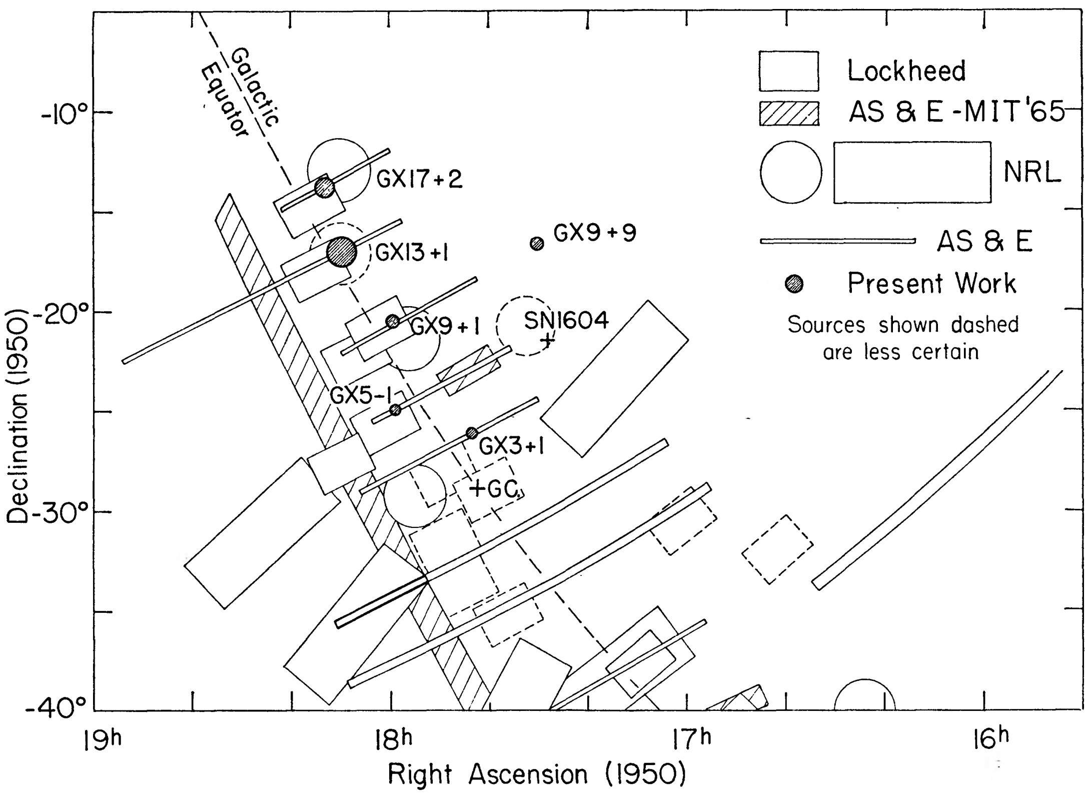

FIG. 6.—Summary of experimental data in the 1–10 keV energy region. The Lockheed and NRL data are taken from the most recent papers of these groups, respectively (Fisher *et al.* 1968; Friedman *et al.* 1967). The AS&E-MIT (1965) data are from Clark *et al* (1965). The present experiment suggests that the AS&E source at $l^{\mathrm{II}} = -2°.5$ lies east of $17^{\mathrm{h}}50^{\mathrm{m}}$, i.e., within the heavy boundaries.

though less likely, *P9* ($\alpha = 16^{\mathrm{h}}23^{\mathrm{m}}.5$, $\delta = -31°34'$). As seen above, the choice of *P7* is consistent with our data only if we invoke a source at *P10* ($\alpha = 17^{\mathrm{h}}46^{\mathrm{m}}.2$, $\delta = -28°10'$).

A summary of experimental results at 1–10 keV is given in Figure 6. The NRL results (Friedman *et al.* 1967) and the Lockheed results (Fisher *et al.* 1968) are shown as dashed lines if they are the less probable source locations reported by those groups. The more certain locations show a correlation with our positions. The earlier AS&E–MIT data (Clark *et al.* 1965) yielded a line of position parallel to and south of the galactic equator ($b^{\mathrm{II}} \simeq -4°$). This could well be the AS&E source GX−2.5 which our data suggest is east of $17^{\mathrm{h}}50^{\mathrm{m}}$ and which was apparently also observed by the NRL group. A comparison of our source intensities with those from the various experiments yields no clear evidence for time variations.

Observations from balloon altitudes at energies above 20 keV have shown a hard, bright source of X-rays in the vicinity of Sgr XR−1 (Boldt *et al.* 1967). Sgr XR−1 is the NRL source region ~4° southeast of GX3+1. Lewin, Clark, and Smith (1968) have very recently reported hard, bright sources in the vicinity of GX3+1 and GX5−1, apparently the same source-region observed by Boldt *et al.* Also, Overbeck and Tananbaum (1968) have reported a bright source in this region.

The radio source MSH 18−13 lies 20′ from the quoted position of GX13+1. It is non-thermal (Large, Mathewson, and Haslam 1961) and has a flux density of 5.3×10^{-26} W m^{-2} Hz^{-1} at 960 MHz. No other radio source in the catalogue of Howard and Maran (1965) lies within any of the error circles for the X-ray source positions. We have communicated the X-ray source positions to optical astronomers in Chile and Australia. The preliminary results of the optical search are given in the following paper. The size of the error circles and the density of optical and radio features in this part of the sky are such that identifications of the X-ray sources must be made with caution. Even in the absence of such identifications, the distribution of X-ray sources within the Galaxy is important to an understanding of the nature of the X-ray sources and, also, to the structure of the Galaxy.

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