Reports

Distribution and Variability of Cosmic X-Ray Sources

Abstract. *At least 30 discrete cosmic x-ray sources have been detected thus far. The distribution is concentrated toward the galactic plane, and most of the sources are believed to lie within 2 kiloparsecs of the sun. It is estimated that the average luminosity of the observed sources is about 5 × 10[36] ergs per second and that the entire galaxy contains about 1250 such sources. Comparisons of fluxes observed over the course of the past 2 years reveal that many sources are highly variable.*

Since the discovery of discrete cosmic x-ray sources in 1962, several surveys have been made by various groups of observers to locate positions and measure fluxes. We now report the locations of 29 sources observed in a survey conducted by the Naval Research Laboratory (NRL) on 25 April 1965 and compare the positions and fluxes with other published observations. Evidence exists of variability in the fluxes from several sources.

Broad sky surveys. The NRL surveys of cosmic x-ray sources have been made with detectors carried aboard unstabilized Aerobee rockets. Mechanical baffles defined the field of view, and the scanning pattern was derived from the roll and precession of the rocket. In the 25 April 1965 flight, the roll rate was 24° per second and the full width at half-maximum transmission of the honeycomb baffle was 8°. The detectors were Geiger counters of the type already described (*1*). Two counters filled to atmospheric pressure with argon plus quench gas provided the data reported here. One counter was equipped with a ¼-mil Mylar window and the other with a 1-mil Mylar window. The different filtration characteristics of the two windows permitted a "two-color" photometric evaluation of spectral quality in the range of 1 to 15 Å.

Figure 1 illustrates typical roll scans. Where the x-ray sources are separated by angles greater than the transmission width of the collimator, a discrete source produces an angular response which is triangular in shape and 8° wide at half-maximum intensity. In regions of the sky where sources are densely grouped, the individual responses are not resolved, and it is necessary to decompose the signal envelopes into individual triangular responses.

From the examples of Figs. 2 and 3, it is evident that the analysis into discrete sources may involve some subjective judgments when the sources are crowded more closely than the 8° half-width of the field of view, and especially when weak sources lie adjacent to strong sources. The uncertainty of position measurement in the roll direction contains contributions from the uncertainty in decomposing the signal envelopes into discrete sources and from mechanical errors of alignment between the x-ray collimator and optical star sensors. The star sensors were also mechanically collimated so that signals in the roll scan could be determined to about 0.5°.

Positions of sources in the pitch directions were determined when the same source could be detected within the field of view on two or more roll scans. The uncertainty in pitch position is directly related to the uncertainty in roll position and is of the same magnitude. Table 1 lists the positions of sources observed in the 25 April 1965 survey, together with the positions reported earlier from NRL surveys in June and November 1964. Also included are the positions of sources reported by Clark *et al.* (*2*) and by Fisher *et al* (*3*). Figure 2 is a plot of the NRL positions from the 1964 and 1965 surveys. Sources which were observed on only a single roll scan are uncertain in pitch position by about ± 4°. These uncertainties are indicated by shaded rectangles which are 8° wide in their long dimension.

The apparent sparseness of sources in the regions of Perseus, Orion, and Centaurus may be only an instrumental effect. The surveys through these regions were performed with apparatus of much lower sensitivity. Sources weaker than one-third the brightness of Tau XR-1 (*4*) were not detectable. In the Cygnus, Scorpius, and Sagittarius regions, the limit of detectability was about one-fifteenth the flux from Tau XR-1.

Distribution of sources. Of the 25 x-ray sources which lie within ± 15° of the galactic plane (Fig. 2), three were observed in the directions of supernova remnants—the Crab Nebula, Cassiopeia A, and the Tycho Brahe supernova of 1572. If these identifications and the generally accepted distances of 1.1 kparsec for the Crab and 3.4 kparsec for Cas A are correct, the computed x-ray luminosities (1 to 10 Å) are roughly equal, about 4×10^{36} erg/sec. Some evidence implies a greater distance to the Crab (*5*), perhaps as great as 1.7 kparsec, and the luminosity estimate would need to increase by about 2.4 times if the greater distance is correct.

According to Minkowski (*6*), the distance to the Tycho Brahe supernova may be as great as 5 kparsec, so that its x-ray luminosity would be about twice as great as that of Cas A. Although the June 1964 NRL survey indicated a source close to the Kepler supernova of 1604, subsequent surveys have not confirmed this observation. The distance to SN 1604 is estimated to be about 8 kparsec. The x-ray flux would be below the sensitivity limit of detection by the instruments of the NRL surveys if SN 1604 were as luminous as the Crab or SN 1572.

Ancient historical records in Japan, Korea, and China (*7*) give positions for a number of supernovae that were sighted in the past 2000 years, besides the well-known trio of the Crab, Tycho, and Kepler. In the region covered by the April 1965 survey, there are six supernovae listed in the oriental records. As shown in Table 1, four are closely positioned to the x-ray sources Cen XR-1, Sco XR-2, Sco XR-5, and Cep XR-3.

Several attempts have been made to infer the nature of x-ray sources from statistical comparisons of their distribution with the distributions of other classes of astronomical objects. The earliest x-ray surveys showed a strong concentration of the sources toward the galactic plane and suggested a search for relationships to disk-population objects such as novae, planetary nebulae, associations of class O and class B stars, thermal radio sources, and galactic clusters. Braes and Hovenier (*8*) called attention to the correspondence of x-ray sources with O-B associations and, in particular, to the proximity of Sco **XR-1** to the nearest association, Scorpius II, at a distance of about 170 parsec. Takakubo (*9*) has noted the clustering around the direction to the galactic center and in the Cygnus region, and suggests that the latter group is composed of "nearby sources" in the Orion-Cygnus spiral arm. Hayakawa *et al.* (*7*) examined the correlation between x-ray sources and ancient supernovae, but found few coincidences. They concluded that the observed x-ray sources are close, about 1 kparsec, and that the lifetime for x-ray emission must be about 40 times as great as for detectable radio emission if the sources are supernova remnants.

The list of Table 1 contains about three times as many sources as the above-mentioned authors considered, so that further statistical comparisons are worthwhile. Referring to Fig. 2, the sources seem to group in two broad clusters close to the galactic plane. Excluding Cas A, nine sources which lie in the Cygnus-Cassiopeia region (l^{II} 60° to 120°) are spaced within an average of ± 7° from the galactic plane. These objects may lie within the Orion-Cygnus spiral arm, of which the sun is a member. If we assume that these sources are distributed in height above and below the galactic plane, like the general stellar distribution, we may take the mean distance from the galactic plane to be about 150 parsec. The average distance of this group of x-ray sources would then be about 1250 parsec. The second broad grouping of x-ray sources centers about the direction to the ga-

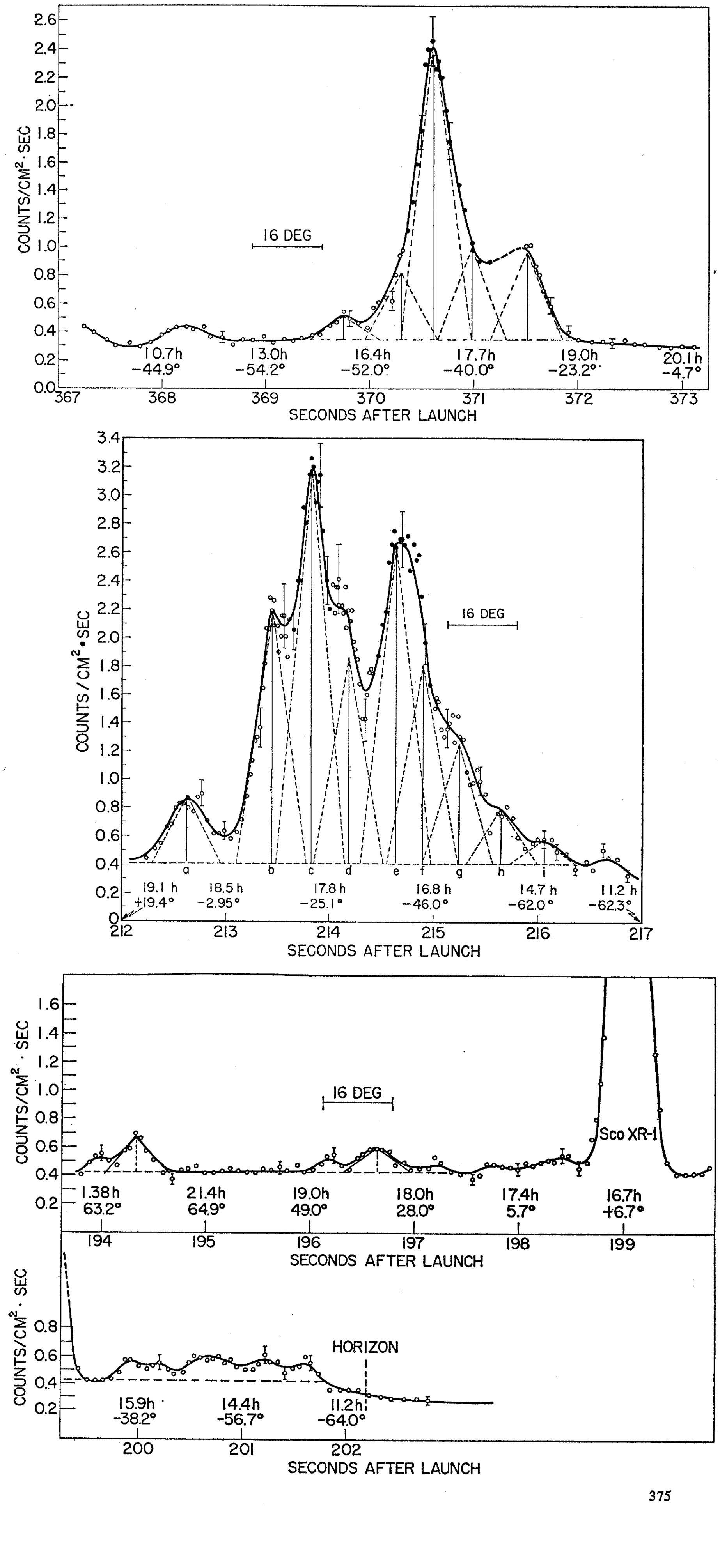

Fig. 1 (right). Representative roll scans from NRL survey, 25 April 1965. Composite envelopes of unresolved sources are decomposed into discrete sources, each characterized by the triangular transmission pattern of the honeycomb collimator. Error bars indicate one standard deviation on the counts per point.

Table 1. X-ray source positions.

Source	α h	α m	δ (deg)	Flux * (count/ cm^2 • sec)	Flux (10^{-8} erg/ cm^2 • sec, 4.0 to 8.0 kev)	Remarks
Cas XR-1 (Cas A)	23	21	+58.5	0.3		
† Tau XR-1 (Tau A)	5	31	+22.1	2.7		
Cep XR-1 (SN 1572)	0	15	+66	0.3		
Ser XR-1	18	45	+ 5.3	.7		
‡ Ser XR-1	18	45	+ 5.3	.7		
Ser XR-2	18	10	−12.9	2.0		
‖ Ser XR-2	18	14	−14.3		0.6	
† Sgr XR-1	17	55	−29.2	1.6		
§ Sgr XR-1	17	48	−30	1.6		
‡ Sgr XR-2	18	10	−17.1	1.5		
‖ Sgr XR-2	18	11	−17.2		0.4	
Sgr XR-3	17	56	−21.6	2.8		
‖ Sgr XR-3	18	03	−20.7		0.7	
§ Sgr XR-4	18	26	−31	0.6		
‖ Sgr XR-5	18	02	−24.9		1.0	
‡ Sco XR-1	16	15	−15.2	18.7		
¶ Sco X-1	16	17.01	−15.53			
Sco XR-1	16	15	−15.0	21		
‡ Sco XR-2	17	8	−36.4	1.4		Nova Sco 827 A.D. (*7*)**
§ Sco XR-2	17	15	−38.4	2.6		16^h50^m, $-43°$
‖ Sco XR-2	17	8	−36.4		1.0	17^h40^m, $-33°$
‡ Sco XR-3	17	23	−44.3	1.1		
Sco XR-4	16	25	−40	0.8		
§ Sco XR-5	17	37	−40.4	.7		Nova Sco 1203 A.D. (*7*) Sharpless 51, CTB37 17^h 40^m, $-40°$
§ Sco XR-6	18	7	−35.6	.3		
‡ Oph XR-1	17	32	−20.7	1.3		
§ Oph XR-2	17	14	−23.5	0.5		
Ara XR-1	17	5	−45.9	1.9		
Nor XR-1	16	24	−51	0.8		
§ Nor XR-2	15	38	−57	.4		
§ Lup XR-1	15	2	−52	.2		
§ Cen XR-1	14	28	−63	.17		B Cen, 185 A.D. (*7*) 13S6A 14^h 20^m, $-60°$
§ Lyr XR-1	18	18	+36	.17		
§ Aql XR-1	19	12	0.0	.13		W-44, 3C 392 (*7*) 18^h 54^m, $+1.2°$
Vul XR-1	20	38	+29	.15		
§ Lac XR-1	22	34	+53.8	.17		
§ Cep XR-2	22	42	+62	.18		
§ Cep XR-3	23	54	+72.9	.15		Nova Cas, 902–930 A.D. (*7*) CT A 1 00^h 03^m, $+72°$
‡ Cyg XR-1	19	53	+34.5	3.6		
Cyg XR-1	19	57	+34.5	0.9		
‡ Cyg XR-2	21	43	+38.8	.8		
Cyg XR-2	21	42	+38.8	1.0		
Cyg XR-3 (Cyg A)	19	58	+40.4	0.4		
§ Cyg XR-4	21	2	+42	.3		
§ Virgo XR-1 (M-87)	12	28	+12.7	.2		
§ Leo XR-1	9	35	+ 8.6	.2		
††Sco X-2	16	50	−39.6			
††Sgr X-1	17	44	−23.2			

* 1 count = 1.2×10^{-8} erg (1 to 10 Å) for bremsstrahlung; $T = 5 \times 10^7$ deg or synchrotron, $\gamma = 1.0$. † NRL survey, November 1964. ‡ NRL survey, June 1964. § Source observed on only one scan; pitch uncertainty ± 4°. ‖ Lockheed survey, 30 September 1965. ¶ Position of optical source identified with Sco X-1. ** Goldstein (*19*) shows that Nova Sco 827 A.D. is a spurious report of SN 1006 A.D. at another position. H. M. Johnson suggests identification with NGC 6302. †† ASE-MIT survey, 26 October 1964.

lactic center (l^{II} 315° to 40°). Fifteen sources, excluding Sco XR-1, lie at an average of ± 3.5° from the galactic plane, and the average distance would appear to be about 2.5 kparsec. These sources may lie in the Sagittarius spiral arm of the galaxy.

The average brightness of the x-ray sources in the Sagittarius group is about 40 percent of that of Tau XR-1 (distance = 1.1 kparsec). If the average distance is about 2.3 times as great as that to the Crab, the average luminosity must be about twice that of Tau XR-1. Similarly, we find for the Cyg-Cas group of sources an average luminosity about 23 percent of that of Tau XR-1. Limited resolution tends to hide from detection any weaker sources in the densely crowded Sagittarius region, more so than in the Cyg-Cas region.

If the distribution of x-ray sources resembles that of galactic novae, the mean distance from the galactic plane is greater, and the estimated distances are proportionately longer. According to Oort (*10*), the mean distances of galactic novae from the plane of the galaxy is about 450 parsec; the computed distances of the x-ray sources would be about ten times greater. It does not seem likely, however, that the average galactic x-ray source would be ten to twenty times as luminous as Tau XR-1.

X-ray luminosity of the galaxy. Taking 2 kparsec as the average distance of the observed x-ray sources, we may estimate the total x-ray luminosity (L) of the galaxy, $L_{\mathrm{Gal}\ (1\ \mathrm{to}\ 10\ \mathrm{Å})}$. If we assume that the galaxy is a uniform, flat, disk-shaped distribution of stars, 15 kparsec in radius, the x-ray sources observed thus far must be confined to about 2 percent of the volume of the galactic disk. We, therefore, estimate the total number of x-ray sources in the galaxy at about

$$25 \times 50 \approx 1250$$

The observed distribution of certain types of disk stars—for example, planetary nebulae, novae, population-II cepheids, and long-period variables—shows a strong concentration toward the galactic nucleus. Large density gradients are observed near the sun. It may be that x-ray sources are similarly concentrated toward the galactic center, and the total number deduced above would need to be increased accordingly. As mentioned earlier, the surveys have been deficient in sensitivity in the range of galactic latitudes from 160° to 320°, which also contributes to an underestimate of the total number of galactic sources.

The average luminosity of a galactic x-ray source in the observed collection, as estimated above, is about 6×10^{36} erg/sec. With 1250 sources corresponding to the range of luminosities thus far observed, the total luminosity of the galaxy is

$$L_{\mathrm{Gal}\ (1\ \mathrm{to}\ 10\ \mathrm{\AA})} \approx 7 \times 10^{39}\ \mathrm{erg/sec}$$

If the galaxy is typical of all spiral galaxies, an isotropic diffuse background x-ray flux should exist. Estimates of this diffuse background have been made by adopting appropriate values for the density of galaxies, n_g, and the distance to the edge of the observable universe, R. Following Gould and Burbidge (*11*), Hayakawa *et al.* (*9*), and Oda (*12*), if

$$n_g \approx 2 \times 10^{-75}\ \mathrm{per\ cm^3},$$

and $R \approx 10^{28}$ cm, the estimated diffuse background x-ray flux is

$$F_{(1\ \mathrm{to}\ 10\ \mathrm{\AA})}\ \mathrm{diffuse} \approx 10^{-8}\ \mathrm{erg/(cm^2{\cdot}sec{\cdot}sterad)}$$

Intergalactic x-ray absorption has been assumed to be negligible.

The observed diffuse flux is 9×10^{-8} erg/(cm²·sec·sterad), almost an order of magnitude greater than the computed integral contribution from normal galaxies. If the x-ray luminosities of galaxies bear a direct relation to radio luminosities, much of the diffuse background may be contributed by the relatively small percentage of peculiar radio galaxies. At least an order of magnitude increase in resolution and sensitivity in the x-ray surveys

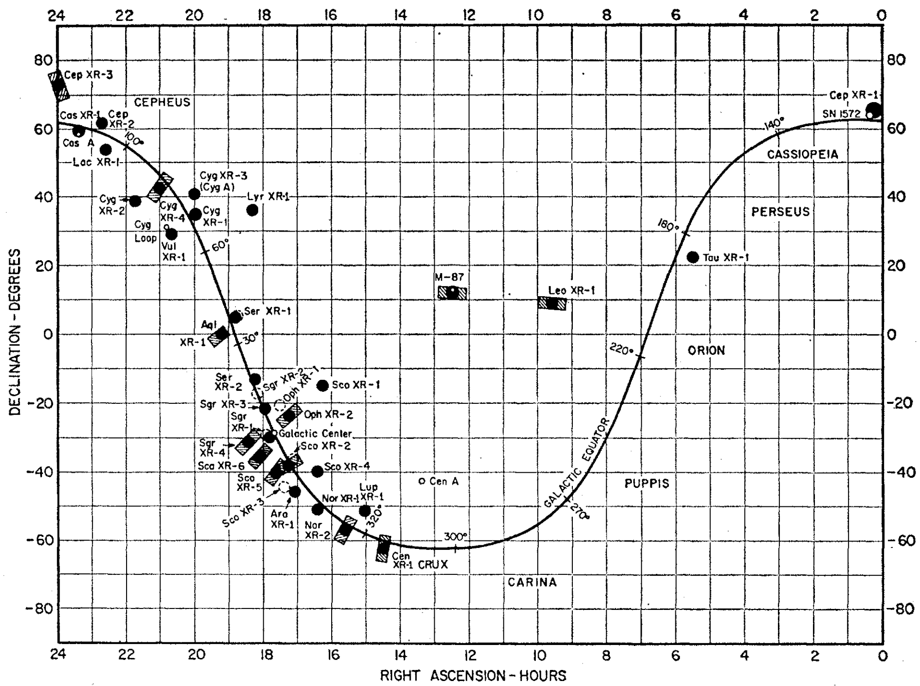

Fig. 2. Map of sources detected in NRL surveys of 1964 and 1965. Estimated uncertainties in position are generally 1.5°. Shaded rectangles indicate 4° pitch uncertainty of positions of sources detected on only one roll scan.

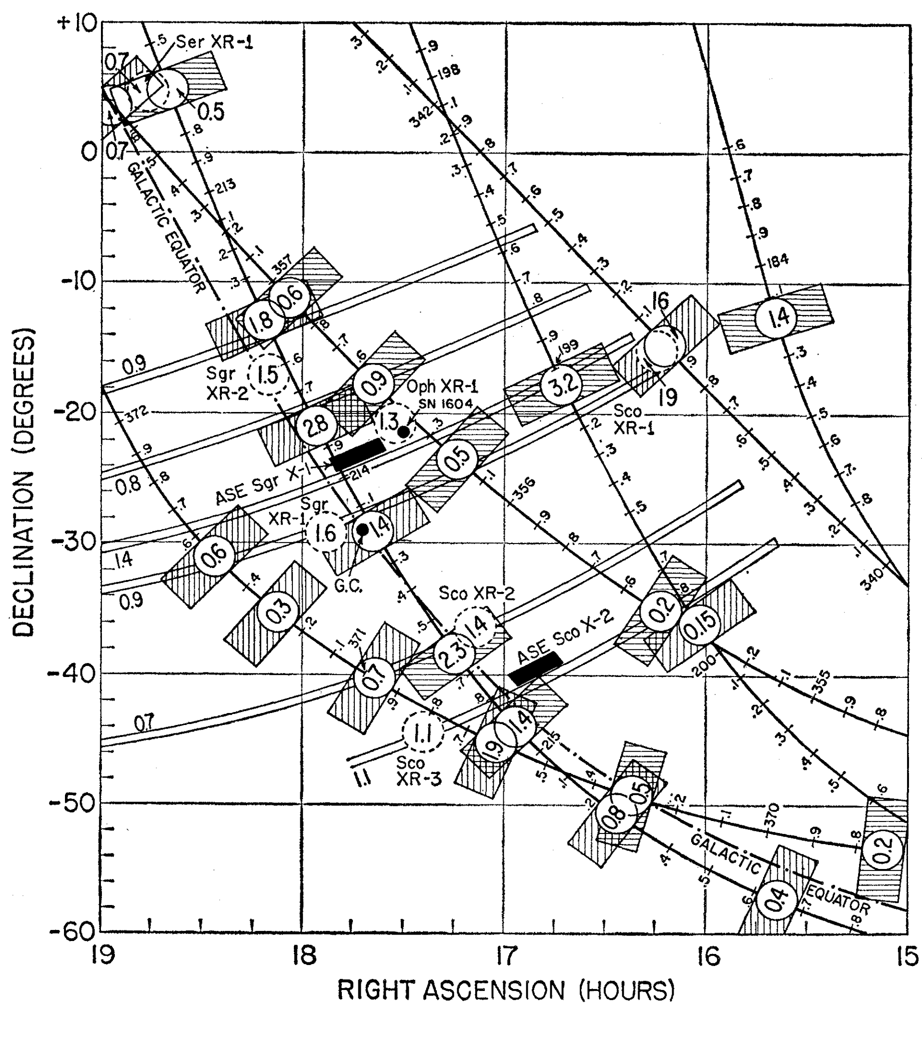

Fig. 3. Scan data from various x-ray surveys. Six roll scans are shown from NRL survey of 25 April 1965. Each track is marked in time from start of flight, as in Fig. 1. Circles give peak positions obtained from analysis of signals such as shown in Fig. 1. Uncertainty of roll position is estimated to be about 1.5°. Pitch position uncertainty is indicated by 8° widths of rectangular boxes. Numbers in circled positions are observed count/cm²·sec. Dashed circles are positions established by earlier NRL survey (16 June 1964). Narrow bands mark positions obtained by Lockheed fan-beam scan 1 October 1964 (*3*). Black boxes gives positions determined by ASE-MIT, August and October 1964 (*2*).

will be needed in order to resolve discrete background sources on a smooth continuum.

Variability of x-ray sources. With the number of surveys of cosmic x-ray sources that has now been made, it is possible to look for evidence of variability. The evidence is to some extent compromised by differences in observing techniques and uncertainties in absolute calibrations; but there are several examples of large variations outside the limits of the observational uncertainties.

Byram, Chubb, and Friedman (NRL) (*13*) have reported observations of the Cygnus region from two flights—16 June 1964 and 25 April 1965—which showed a 75-percent decrease in flux (1 to 10 Å) from Cyg XR-1. Fisher *et al.* (*3*) observed the same source in September 1964 and reported a counting rate only one-sixth that of the NRL June 1964 flux. The NRL detector was more sensitive at long wavelengths than that flown by Fisher *et al.* However, if one allows a factor of 2 in sensitivity, it appears that Cyg XR-1 decreased in brightness by at least a factor of 3 in less than 3 months.

The NRL surveys found less than 20 percent difference in the brightness of Cyg XR-2 (1 to 10 Å) between June 1964 and April 1965. McCracken (*14*) observed the Cygnus region from a balloon on 2 April 1965 in the energy range near 25 kev. Although a strong signal was observed from Cyg XR-1, none was detected from Cyg XR-2. In the range (1 to 10 Å) the NRL group found Cyg XR-2 comparable in brightness to Cyg XR-1, and its spectrum was harder, which would lead one to expect relatively higher flux at higher energies. Balloon measurements by Brini *et al.* (*15*) on 31 March 1966 and 2 April 1966 observed comparable fluxes (20 to 180 kev) from Ser XR-1 and Cyg XR-2, about 5×10^{-8} erg/cm$^2\cdot$sec, but no evidence of Cyg XR-1. They placed an upper limit on the flux of Cyg XR-1 at only 10 percent of Cyg XR-2 and Ser XR-1. It appears that the Cygnus region sources, XR-1 and XR-2, are highly variable on time scales as short as 1 month.

The region of the galactic plane, l^{II} 320° to 40°, has been searched several times between 1962 and 1966. Figure 5 is an attempt to illustrate the results of some of these observations. Six tracks are shown of the NRL scans of 25 April 1965. Shaded rectangles along these tracks represent positions where sources are deduced from signal records, such as shown in Fig. 1. Each rectangle is 1.5° wide in the scan direction to indicate the uncertainty in roll position, and 8° long to indicate the uncertainty in pitch position. Where a source is detected on two or more adjacent roll scans, its pitch position can be determined (Table 1). The numbers inside the 1.5° circles are the observed count fluxes. Results of the November 1964 NRL survey are shown as dashed circles. Certain major differences between these two NRL surveys are apparent. Sources Sgr XR-2, Oph XR-1, and Sco XR-3 appeared in 1964 but not in 1965. Sources listed as Sgr XR-3, Ser XR-2, and Ara XR-1 appeared strongly in 1965 but not in 1964.

On the basis of the two NRL surveys alone, some reservation would be justified in attributing these differences to variability, since the 1965 survey was conducted with much higher sensitivity, and the complex of sources could be better resolved. However, when further comparison is made with the observations of Fisher *et al.* (Lockheed) (*3*) and of Clark *et al.* (ASE-MIT) (*2*), the differences take on more significance. In Fig. 3, the results of the fan-beam scan by the Lockheed group are shown as narrow strips whose widths represent the roll resolution and whose lengths represent the pitch field of view. No source was found in 1964 through the position of Sgr XR-2, but fairly good agreement occurs for Ser XR-2, Sgr XR-3, Sgr XR-1, Sco XR-2, and Sco XR-3. A similar survey (*16*) was performed on 30 September 1965, which then showed a strong source at Sgr XR-2 but none at Sgr XR-1. Finally, the two black boxes of Fig. 3 are positions reported by the ASE-MIT group (*2*) for Sgr X-1 and Sco X-2 in August and October 1964. There is no apparent fit with the NRL observations and no positive correlation with the Lockheed observations.

One may conclude from the observations cited above that variability is a prominent feature of many of the x-ray sources thus far detected. Sco XR-1 has been identified with a blue starlike object, possibly an old nova (*17*), but no conclusive evidence has yet been obtained for variability of its x-ray emission. Shklovsky (*18*) has proposed that it is a binary system, one component of which is an old neutron star whose core has cooled to a low temperature. The strong gravitational field of the neutron star acts as a sink which accretes gas from its companion star. The kinetic energy of the in-falling gas would be sufficient to provide the x-ray emission of the high-temperature plasma which surrounds the neutron star.

A large fraction of old novae are known to be eclipsing binaries. Shklovsky's neutron star model would permit a wide range of variability if the binary system were eclipsing. It is clearly important to conduct continuous x-ray observations from satellites if the full nature of x-ray source variability is to be revealed.

H. Friedman
E. T. Byram
T. A. Chubb

E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D.C. 20390

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