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THE DISTRIBUTION OF THE GALACTIC COMPACT X-RAY SOURCES: A STATISTICAL ANALYSIS

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ABSTRACT

A statistical analysis of the distribution in galactic longitude of the compact galactic X-ray sources listed in the *Uhuru* catalog shows that the distribution is not significantly inconsistent with a uniform space distribution of the sources throughout the galactic disk, provided that, as usually assumed, the *Uhuru* sample is complete for $L_x \geqslant 10^{36}$ ergs s^{-1}. In this scenario, however, there is a significant excess of sources at small distances from the Sun.

Upon examining the matter of completeness of the *Uhuru* sample, it is found that a source having $L_x = 10^{36}$ ergs s^{-1} could not be detected from a distance beyond the galactic center, and only sources having $L_x \geqslant 10^{37}$ ergs s^{-1} should be detectable everywhere in the Galaxy. We thus conclude that a significant number of weaker sources should be found by a detector with a better angular resolution than the *Uhuru*, and that the concentration of sources at longitudes near the galactic center reflects a real concentration of the sources toward the center of the Galaxy.

Subject headings: galaxies: structure — X-ray: sources

I. INTRODUCTION

Among the generally accepted properties of the galactic compact X-ray sources are those of their distribution in the Galaxy. Salpeter (1973) and Gursky (1973) both studied the distribution in galactic longitude of these sources and concluded that the observational evidence seems to support a strong concentration in the vicinity of the nuclear bulge of the Galaxy, i.e., between $320° < l < 20°$ (see also Blumenthal and Tucker 1974).

A second currently accepted fact is that we see *all* the galactic sources with $L_x \geqslant 10^{36}$ ergs s^{-1} in the range 2–10 keV (Blumenthal and Tucker 1974).[1] $L_x \approx 10^{36}$ ergs s^{-1} is also the lower bound of the X-ray luminosity of the sources considered here.

Since, as remarked by Gursky (1973), when one looks toward the galactic center one actually looks through the bulk of the Galaxy, and all of the sources are seen, it is valid to ask to what extent the observations demand that the sources be physically concentrated toward the nucleus of the Galaxy. This is done in § II.

In § III we examine the distribution of X-ray sources near the sun. Section IV considers the completeness of the sample, and § V presents the results and discussions.

II. THE GALACTIC DISTRIBUTION OF SOURCES

Out of the 160 sources in the Third *Uhuru* Catalog (Giacconi *et al.* 1974), we selected a sample of 59 sources which must be galactic according to the criteria adopted by Gursky (1973), namely: (1) flux greater than 8 counts s^{-1}; (2) source not identified with an external galaxy, supernova remnant, or transient source; (3) $|b| < 20°$, except for well-identified sources at higher galactic latitudes. The resulting sample is very similar to that of Gursky (1973): five new sources have been added, while one has been deleted due to a revised source strength.

As observed previously (Salpeter 1973; Gursky 1973), the selected sources are highly concentrated at low galactic latitudes. We shall now compare the actual longitude distribution with the expected distribution under the assumptions that (1) the total number of sources is 59; (2) the sources are uniformly distributed in the galactic plane.

The distance from the galactic center to the Sun has been taken to be 10 kpc, and we have computed the distribution for two values of the galactic radius, $R = 12.5$ kpc, and $R = 15$ kpc. The surface densities are then 0.12 sources kpc^{-2} and 0.08 sources kpc^{-2}, respectively.

The results are shown in Figure 1, together with the observed source distribution. We have plotted the number

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[1] Notice, however, that in the original work by the *Uhuru* group (Matilsky *et al.* 1973), only an *essentially* complete coverage is claimed on the basis of statistical arguments which indicated a low population of sources having luminosities near the lower bound.

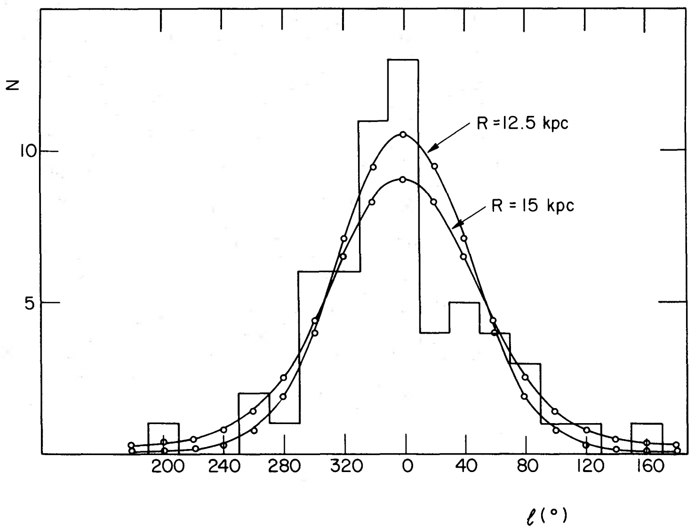

FIG. 1.—Observed distribution of galactic X-ray sources. Shown are the number of sources in the range $l - 10°$ to $l + 10°$ as a function of l. Also shown are the expected distributions, assuming a uniform surface density of sources in the galactic disk, for two values of the galactic radius R.

Note that the distribution for $R = 15$ kpc seems to be a better fit to the number of sources observed in the direction of the galactic anticenter. The total number of sources is 59.

of sources observed in the range $l - 10°$ to $l + 10°$ as a function of l, starting from $l = 0$, and using steps of 20°. The excess, if any, in the direction of the galactic center is given by the number of observed sources above the expected distribution in that direction. We can see that, for a galactic radius of 15 kpc, we have an "excess" of six sources, whereas for $R = 12.5$ kpc, this number reduces to three. Notice also that in this sampling mode, we see no special concentration of sources in the direction of the spiral arms.

In view of the small number of the sample, it is worth looking at the problem on a statistical basis. Are the observed deviations from a uniform suface distribution larger than those expected from sampling fluctuations?

We have used the χ^2 test to examine the hypothesis of uniform surface distribution for the X-ray sources. To get meaningful results, we have, when necessary, combined two or more consecutive bins to get an expected number of sources larger than three (Ostle 1963). The χ^2 values obtained by this method are 7.3 (8 degrees of freedom) for $R = 12.5$ kpc and 5.6 (9 degrees of freedom) for $R = 15$ kpc. These yield respective probabilities of 0.5 and 0.8 of observing χ^2 values as large as or larger than the ones observed here. Hence, we conclude that a uniform surface distribution of these 59 sources cannot be rejected on purely statistical arguments.

III. THE X-RAY SOURCES NEAR THE SUN

If all of the galactic compact sources were the 59 of the sample referred to earlier, the density of sources would be 0.08 to 0.12 per kpc^2, depending on the value chosen for the galactic radius. If we allow the possibility that our selection criteria are much too restrictive, we can increase the number of galactic compact sources to 100. In this case, the density reaches the range between 0.15 and 0.20 sources per kpc^2. Let us compare these numbers with the source density near the Sun.

We have listed in Table 1 the five sources which, at this time, are thought to be located within 2 kpc from the Sun. Note that this number is probably a *lower limit*, since other sources may be found within 2 kpc once distance estimates become available for all of the sources. We see that at least three sources are within 1 kpc, and five are within 2 kpc. In the following argument we exclude the source 3U 0352+30 ≡ X Persei, because (*a*) the identification is not fully confirmed and (*b*) if the objects are related, $L_x \ll 10^{36}$ ergs s^{-1}, and so the object is of a type different from those considered here. With the maximum source density of 0.2 sources per kpc^2, we can now compute the probability of finding at least 2 sources within 1 kpc (≤ 0.6 are expected) and at least 4 within 2 kpc (≤ 2.4 are expected). These probabilities are, using a Poisson distribution, less then 0.11 and less than 0.13, respectively. While these numbers are not negligible, and so the concentration of sources near the Sun may indeed be a sampling fluctuation, they are small enough to warrant examining an alternative explanation, namely that we do not see all of the galactic sources having $L_x \geqslant 10^{36}$ ergs s^{-1}. If the total number of galactic compact sources were, say, 150 instead of 100, no significant concentration would exist near the Sun. This would occur if, for example, the interstellar absorption, plus the geometrical dilution of the radiation originating in a significant number of the intrinsically weaker sources at large distances from us, reduced their flux at Earth to levels below the threshold of the detectors in the *Uhuru* satellite. We shall examine this point in the following section.

TABLE 1

GALACTIC X-RAY SOURCES WITHIN 2 KILOPARSECS OF THE SUN

3U Designation	Name	Optical Candidate	Distance (kpc)	Reference
1617−15...........	Sco X-1	...	0.2–1	*a, b, c, d*
2142+38...........	Cyg X-2*	...	0.5–0.7	*e, f*
0352+30...........	X Per†	HD 24534	0.3	*g, h, i, j*
1700−37...........	...	HD 153919	1.7	*k*
0900−40...........	...	HD 77581	1.2	*l, i*

* Identification not fully confirmed.

† Not included in the statistics.

REFERENCES.—(*a*) Hiltner and Mook 1970. (*b*) Gatewood and Sofia 1968. (*c*) Sofia *et al.* 1969. (*d*) Wallerstein 1967. (*e*) Kraft and Demoulin 1967. (*f*) Giacconi *et al.* 1967. (*g*) van den Bergh 1972. (*h*) Braes and Miley 1972. (*i*) Brucato and Kristian 1972. (*j*) Wackerling 1972. (*k*) Jones *et al.* 1973. (*l*) Hiltner *et al.* 1972.

IV. THE COMPLETENESS OF THE *UHURU* SAMPLE OF GALACTIC SOURCES

The limit of detectability of the instruments on the *Uhuru* satellite is ≥ 2 counts s^{-1}. The spectrum of a typical galactic source can be expressed in terms of thermal bremsstrahlung after undergoing interstellar absorption. This can be expressed as

$$N_p(E) = A \exp(-E/kT) \exp[-\sigma(E)N_{\rm H}] \text{ photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}, \quad (1)$$

where E is energy, k is the Boltzmann constant, T the temperature, $\sigma(E)$ is the effective attenuation cross section per hydrogen atom, and $N_{\rm H}$ is the column density of hydrogen atom (Hayakawa 1973). A is the normalization factor which relates the spectrum to the luminosity of the source.

Typical parameters for the galactic sources are: $kT \approx 5$ keV; $N_{\rm H} = \langle\rho\rangle d \approx 0.2d$ cm^{-2}. It can be shown that $A \approx 0.394\, L_x(36)/r^2$, where $L_x(36)$ is the X-ray luminosity in units of 10^{36} ergs s^{-1}, and r is the distance (in kpc). Also,

$$\sigma(E) = 2.0 \times 10^{-22} \left(\frac{1\text{ keV}}{E}\right)^{2.5} \text{cm}^2 \text{ for } E \geq 0.53 \text{ keV} \quad (2)$$

(Brown and Gould 1970). The total X-ray flux at the Earth is

$$F(r) = \int_{2\,keV}^{10\,keV} AE \exp(-E/kT) \exp(-\sigma(E)N_{\rm H})dE \quad (3)$$

$$F(r) = 4A \int_{-1}^{1} (4y + 6) \exp[-0.2(4y + 6)] \exp[-0.123r/(4y + 6)^{2.5}]dy\,. \quad (4)$$

The number photon flux is (Giacconi *et al.* 1974)

$$n\,(\text{counts s}^{-1}) = \frac{F(r)}{1.7 \times 10^{-11}}\,. \quad (5)$$

Performing a Gauss-Laguerre 4-point integration, we obtain

$$n \approx 1.483 \times 10^2 \frac{L_x(36)}{r^2} [0.497 \exp(-4.487 \times 10^{-4}r) + 0.533 \exp(-1.17 \times 10^{-2}r) + 1.10$$
$$\times \exp(-8.73 \times 10^{-4}r) + 1.196 \exp(-2.652 \times 10^{-3}r)] \text{ counts s}^{-1}\,. \quad (6)$$

The results of this calculation are displayed in Figure 2, where we plot the expected photon count as a function of distance for different values of the X-ray luminosity of the source. It is worth noting here that the absorption correction is always less than about 15 percent, whereas the denominator of equation (5) is uncertain by about 30 percent, and also depends on the exact spectral shape. Consequently, the absorption considerations can be ignored, although they were included in our Figure 2.

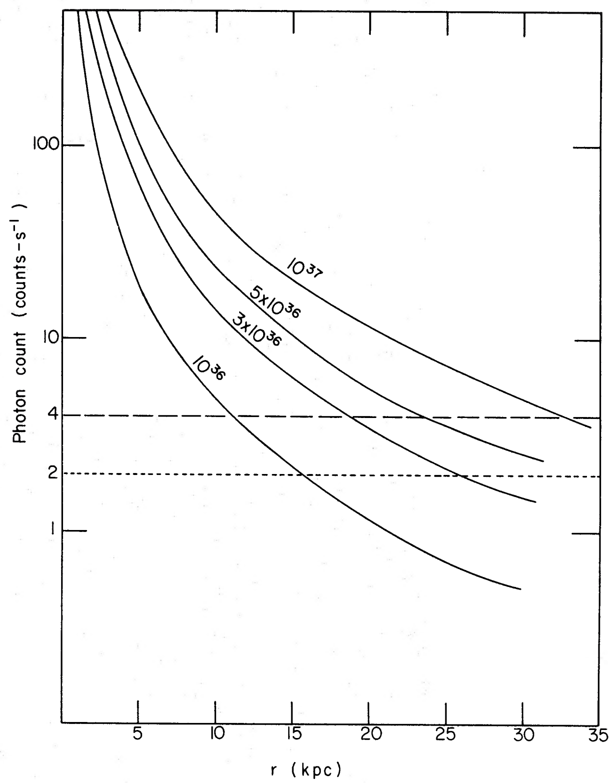

FIG. 2.—Expected photon count as a function of distance for different values of the X-ray luminosity of the source. The dashed line is a practical threshold of the *Uhuru* detectors for crowded fields, whereas the dotted line is the limit of detectability. Luminosities are in ergs s^{-1}.

V. RESULTS AND DISCUSSION

By inspecting Figure 2, we can see that sources having luminosities of 10^{36} ergs s^{-1} cannot be seen beyond the galactic center, whereas when the luminosity is 10 times as large, it should be seen from anywhere in the Galaxy. We have assumed in the figure that the weakest detectable sources have 4 counts s^{-1}, although the *Uhuru* instruments are really sensitive down to 2 counts s^{-1}. This was done since these sources concentrate near the galactic center, where source confusion raises the effective detection threshold. Obviously, then, the *Uhuru* satellite is missing some of these weaker sources, and none of them should be missed by instruments with greater angular resolution. In order to estimate exactly how many sources are being missed, it would be necessary to know the distribution of luminosities of the galactic sources, a datum which we do not currently have with sufficient reliability. Moreover, since we are missing the weaker sources at large distances, we are missing proportionately a larger fraction in the direction of the galactic center than we do in any other direction.

Consequently, accounting for the excess of sources near $l = 0°$ is no longer possible on geometrical considerations alone, and a physical space density concentration near the galactic nucleus is still necessary.

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