

NASA TM X-70541

70541

X-661-73-361

PREPRINT

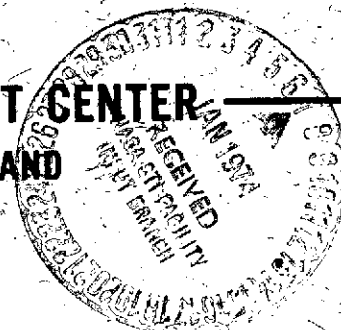
ON THE NATURE OF THE UNIDENTIFIED HIGH LATITUDE UHURU SOURCES

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NOVEMBER 1973

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND



N74-13535

Unclas
G3/29 24656

(NASA-TM-X-70541) ON THE NATURE OF THE
UNIDENTIFIED HIGH LATITUDE UHURU SOURCES
(NASA) 18 p HC \$3.00
CSCL 04A

ON THE NATURE OF THE UNIDENTIFIED
HIGH LATITUDE UHURU SOURCES

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ABSTRACT

It is found that the unidentified high latitude UHURU sources can have either of two very different explanations. They must either reside at great distances with luminosity $\geq 10^{46}$ ergs/sec, or be contained in the galaxy with luminosity $\leq 10^{34}$ ergs/sec. The two possibilities are indistinguishable with the available data.

I. INTRODUCTION

The UHURU catalog of x-ray sources (Giacconi, et al. 1973) lists 64 sources at high galactic latitude ($|b| > 20^\circ$). Of these, two are known to be associated with galactic objects (SCO X-1 and HER X-1), while nineteen have been associated with specific extragalactic objects. These have been broadly categorized into two main classes: those called "compact" sources associated with single unusual galaxies (e.g. radio galaxies, Seyferts, quasars), and more

extended sources associated with clusters of galaxies (the great majority of identified extragalactic objects).

The remaining forty-three high latitude sources are, as yet, unidentified. The consistency of this sample with an extragalactic hypothesis has led to the speculation that many (if not all) of these sources are extragalactic (Giacconi, et al. 1971, Murray, et al. 1972, Matilsky, et al. 1973). As the unidentified sources constitute approximately two-thirds of the total sample of high latitude sources, conceding them an extragalactic nature implies that the bulk of the x-ray emission in the local epoch of the universe may have its origin in galaxies which are undistinguished in other electromagnetic bands. Searches of the location error boxes of these objects have yielded no positional associations with classes of extragalactic objects which are known to be x-ray sources (Murray, et al. 1972), so that, if proven extragalactic, they constitute an entirely new category of x-ray emitters.

Alternatively, Bleach, et al. (1972) have suggested that low luminosity sources in the galaxy may be responsible for the excess ≥ 2 -keV emission which they observe in the galactic plane at $l \approx 60^\circ$. These objects, with an emissivity of $\sim 10^{33}$ ergs/sec and a scale height of a few hundred parsecs, could conceivably replicate the characteristics of the unidentified high latitude sources. Holt, et al. (1973) have emphasized the plausibility of this conjecture.

Using further data from UHURU, we have attempted to determine if either of these hypotheses can be shown to be inconsistent with

the observations. We find that we cannot unambiguously distinguish between these two possibilities, but that we can place constraints on the physical properties of either galactic or extragalactic populations which might contribute to the source sample.

II. DISCRETE SOURCE MEASUREMENTS

The positive evidence in favor of an extragalactic hypothesis is the consistency of the observed distributions with those expected. Matilsky, et al. (1973) have demonstrated this for sources with $|b| > 20^\circ$ and of apparent strength $S \geq 3$ cts/sec in the 2U catalog, and this consistency is actually even better down to $S \geq 2$ cts/sec using the 3U catalog.

The latitude distribution of the unidentified $|b| > 20^\circ$ sources is shown in Figure 1. Plotted is the source density per unit solid angle corrected for survey coverage and sensitivity for a) all the unidentified sources, and b) the sources weaker than 4 cts/sec. Isotropy would be expected for extragalactic sources, and also for galactic sources provided that the source horizon (the distance to which the weakest source is observed) is within the source scale height. Examination of the weakest sources (which should be, on the average, the most distant) is the most likely place to find a correlation with the galactic disk, and none is evident from Figure 1b.

Similarly, the coverage corrected longitude distribution is consistent with isotropy, with a galactic-center-to-anticenter ratio of $\sim 1:1$. Extreme population II objects such as globular clusters give a ratio of $\sim 5:1$, (for $|b| > 20^\circ$) so that the

alternative local source hypothesis must be constrained by a scale height which does not exceed a few kpc to match the measured fore-aft ratio of unity.

The intensity distribution of the unidentified sources is shown in Figure 2. The plot 2a is an integral representation of the data (corrected for coverage) compared with the $N(>S) \propto S^{-3/2}$ expected from a uniform population of sources in the non-evolutionary metagalaxy. The plot 2b is a differential representation of the same data which, unlike the more conventional representation 2a, allows for the explicit independence of each data point. Although the overall fit with a uniform source density is reasonable, there are at least three remarks which should be noted prior to drawing any conclusions from this distribution. First, and perhaps most obvious, is the statistically significant lack of very strong ($S > 10$ cts/sec) sources. Second, there is the danger of contamination of the low intensity portion of the distribution by fluctuations arising from sources below threshold which can masquerade as point sources just above threshold. Third, the dynamic range of the distribution is not terribly large to begin with, and is reduced even more if the high and low intensity points are removed from consideration.

III. GALACTIC EMISSION

The best argument in favor of an extragalactic origin for the unidentified sources is a compelling argument against a local origin.

We must therefore, consider the impact of observable parameters associated with possible galactic emission. If the unresolved X-ray emission observed by any detector is assumed to arise from extragalactic "diffuse sky background" (measured through the appropriate thickness of cold galactic matter), plus some contribution from discrete galactic sources, the surface brightness of any patch of sky is given by:

$$\frac{dI}{d\epsilon} \text{ cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1} \text{ sr}^{-1} = \frac{dj}{d\epsilon} \frac{n_s}{4\pi} \int_0^D e^{-\sigma(\epsilon)n_H r} dr + e^{-\sigma(\epsilon)n_H D} \left\{ \frac{dI_x}{d\epsilon} + \frac{dj}{d\epsilon} \frac{n_s}{4\pi} (d-D) \right\}, \quad (1)$$

where $\frac{dI_x}{d\epsilon}$ = extragalactic diffuse background ($\text{cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1} \text{ sr}^{-1}$)

n_H = mean hydrogen density along the line of sight (cm^{-3})

D = distance through hydrogen along the line of sight (cm)

d = distance through source distribution along the line of sight ($\geq D$)

$\sigma(\epsilon)$ = cross-section for photo electric absorption per H atom at energy ϵ in the interstellar medium (cm^2)

$\frac{dj}{d\epsilon}$ = average source differential emissivity ($\text{sec}^{-1} \text{ keV}^{-1}$)

n_s = average source density (cm^3).

Equation (1) may be simplified considerably by assuming that the integrated source contribution at any longitude scales with the columnar hydrogen density $N = n_H D$ in the plane (but not necessarily perpendicular to the plane). Since $\sigma n_H D < 1$ in any direction at energies above 2 keV, we can expand the exponential to first order and ignore the absorption of the local source contribution, giving

$$I_{\text{net}} = I|_{\theta=0} - I|_{\theta=\frac{\pi}{2}} = N \left\{ \frac{j n_s}{4\pi n_H} - \int_2^{10} \sigma(\epsilon) \frac{dI}{d\epsilon} d\epsilon \right\}. \quad (2)$$

Note that the sign of I_{net} is independent of N in this simplified model, so that Equation (2) can be rewritten in a form which is independent of galactic longitude in the plane by means of a parameter $\kappa \equiv 10^{22} \times I_{\text{net}} / N$

$$j n_s = 4\pi n_H \left\{ \frac{I_{\text{net}}}{N} + 5.6 \times 10^{-23} \right\} = 8.8 \times 10^{-22} \{ \kappa + .56 \}, \quad (3)$$

where we have taken $n_H = 0.7 \text{ cm}^{-3}$, $\sigma(\epsilon) \approx (4 \times 10^{21} \epsilon^3)^{-1} \text{ cm}^2$ from Brown and Gould (1970) and $\frac{dI}{d\epsilon} = 8 \epsilon^{-1.4} \text{ cm}^{-2} \text{ sec}^{-2} \text{ keV}^{-1} \text{ sr}^{-1}$ from Boldt, et al. (1969).

Using the standard UHURU conversion factor $1 \text{ ct/sec} = 1.7 \times 10^{-11} \text{ ergs cm}^{-2} \text{ sec}^{-1}$ (2-10 keV), and taking 4 keV as the mean photon energy, equation (3) can be used to determine the total number of sources in a sphere of radius equal to the source horizon, as a function of κ . Taking $S_{\text{min}} = 2 \text{ cts/sec}$, and considering that the present sky coverage and sensitivity imply that $\sim 4/9$ of these sources are presently observed at $|b| > 20^\circ$, we obtain

$$N_{\text{obs}} = 76 (\kappa + .56) R_H (\text{kpc}), \quad (4)$$

where N_{obs} is the number of $|b| > 20^\circ$ sources expected to be observed at a level $S \geq 2 \text{ cts/sec}$ with the source horizon at R_H . This relation is plotted in Figure 3, and represents the number of sources expected to be presently classified "unidentified high latitude sources", if the source horizon is within the source scale height (as demanded by the latitude isotropy of the sample). The $\pm 1\sigma$ uncertainty band shown in Figure 3 reflects only the counting statistics in 43 sources, and

does not include the $\sim 20\%$ representative of the uncertainty in sky coverage. Note that the observed number of unidentified sources can be reconciled with a local origin even if $\kappa \leq 0$ (i.e. even if a decreased, rather than increased, intensity is observed in the plane relative to the pole), provided that these local sources have a scale height of the order of 1 kpc. This is an important point which was not appreciated by Matilsky, et al (1973) in arguing the case for an extragalactic hypothesis.

IV. . DIFFUSE X-RAY MEASUREMENTS

Measurements of I_{net} can only be made directly with detectors having a field of view $\lesssim 2^\circ$ perpendicular to the galactic plane. For larger apertures, each of the two terms in Equation (2) must be properly evaluated from the detector characteristics. In the absence of any local sources, this means that the UHURU $5^\circ \times 5^\circ$ detector should experimentally measure a galactic plane "ridge" of approximately -1 ct/sec per 10^{22} H-atoms cm^{-2} in the line of sight. Therefore, the best measurements of κ should be made in directions for which N is largest, as all directions should yield the same κ consistent with the simplified source distribution assumed in the model. Unfortunately, these are also the regions for which the possibility of strong source contamination is highest and, in fact, the lowest upper limits for κ are obtained in the directions of minimal N . The 3σ upper limits obtained from UHURU at $\ell \sim 250^\circ$ and $\ell \sim 165^\circ$ can be expressed in terms of the formalism of the galactic model as implying that $\kappa \lesssim 1/2$ (these are directions for which $N < 10^{22} \text{ cm}^{-2}$, cf. Daltabuit and Meyer 1972). UHURU data in other directions, as well as rocket-borne experimental data (Bleach, et al. 1972), indicate that measured values of κ may

be larger (but not smaller) than the above limits. The most conservative assumption which we can make in testing the local source hypothesis, therefore, is that those other measurements may be contaminated by contributions from strong sources (i.e. not by sources of the type at issue here).

There is further unresolved X-ray data relevant to the present study, in the form of the observed fluctuation spectrum of the sky background viewed by UHURU. Schwartz has emphasized the importance of such a measurement in the determination of the characteristics of discrete sources which might contribute to the sky background (Schwartz 1970, Schwartz, et al. 1971, Schwartz and Gursky 1973). For a superposition of discrete sources assumed to be uniform (and corrected for red shift at large distances), the expected ^{variance} measured by the UHURU detector should be

$$(\delta S)^2 \geq \frac{3\Omega}{4\pi} N_s S_{\min}^2 \quad (\text{cts/sec})^2, \quad (5)$$

where Ω is the detector solid angle, and N_s is the total number of sources in the spherical volume bounded by S_{\min} . The published UHURU data with which this may be compared are displayed in Figure 12 of Kellogg (1973), wherein a point-to-point correlation was performed of diffuse background taken continuously as the $5^\circ \times 5^\circ$ detector scanned. The bin boundaries were taken each 5° on the scan path, so that the data in adjacent bins are not completely independent. Correcting for this non-zero correlation, and considering all possible uncertainties in N_s , equation (5) demands that the measured total variance should be greater than unity, while the experimental value is only

$(0.6)^2$. Even before considering effects which can only increase the experimental variance (such as photon statistics and varying non-X-ray background), this discrepancy requires that the unidentified high latitude sources cannot be members of a uniform extragalactic population. This point is quite independent of the fraction of the total sky background which might arise from discrete extragalactic sources.

V. DISCUSSION

There are two categories of experimental data which are applicable to the present issue: measurements of resolved discrete sources, and measurements of diffuse x-radiation which we can attempt to interpret in terms of unresolved discrete sources.

The former category of information implies that the unidentified sources in question are (at the present level of detectability), statistically consistent with:

1. Isotropy in galactic longitude
2. Isotropy in galactic latitude
3. Uniformity in space density (except very locally).

The latter category of information can be expressed as departures from the zeroth order uniform-density extragalactic model as:

4. Lack of expected measurable spatial fluctuations
5. Lack of measurable absorption in the galactic plane.

The first two conditions are prerequisites for an extragalactic hypothesis, and can be reconciled with a local hypothesis if the present source horizon is within the scale height of the source distribution;

this means that local sources which might contribute to this sample have luminosities ($\leq 10^{34}$ ergs/sec) at least two orders of magnitude below those of the objects in our galaxy which would ordinarily be termed x-ray sources.

The third condition must be considered carefully. The lack of high intensity sources is an embarrassment for the local hypothesis, as the postulation of a very local source-poor region is completely ad hoc. The assumption of a source-free neighborhood for an extragalactic hypothesis is, likewise, ad hoc, but it is conceivable that such a deficiency in the local epoch may be attributable to a true model constraint instead of a local density fluctuation.

If uniformity in spatial density were to continue past the "threshold" defined by the high intensity deficiency, we would expect the intensity distribution to be steeper than $S^{-3/2}$ at the lowest intensities if the sources were extragalactic. This is because we expect that some of the source fluctuations below the limiting source sensitivity should masquerade as low intensity sources. On the other hand, local sources should not exhibit this effect if the source horizon is a substantial fraction of the source scale height. Point 4. is immediately applicable to the extension of this discussion, as a uniform extragalactic population is unconditionally denied by the fluctuation data. This limit is so strong that a wholly extragalactic explanation for the unidentified high latitude sources can have only two possibilities: a "thin" shell of sources (where the thickness of the shell cannot be much larger than its inside radius), or an entirely

cosmological source sample. As the former possibility must have its origin in an evolutionary effect, the two possibilities converge to a source population with average luminosity $\geq 10^{46}$ ergs/sec.

On the other hand, Point 5. indicates that no measurement of which we are aware has demonstrated that $\kappa < 0$. If $\kappa > -0.56$, emission from the galactic plane is required. If this emission arises from discrete sources, it is possible to construct a source distribution which completely satisfies all five experimental effects. Our best estimates on the basis of the present data are an average source luminosity of $\approx 10^{34}$ ergs/sec with a scale height of ~ 1 kpc (similar to that suggested by Gorenstein and Tucker (1972) to explain the low energy x-ray excess off the galactic plane). The total luminosity of all such sources in the galaxy, if they are completely responsible for all of the unidentified high latitude sources, is $\approx 10^{39}$ ergs/sec. It is important to note that this total luminosity is comfortably small, in order that it not conflict with the observed emission from nearby galaxies such as the LMC (which emission is dominated by a few discrete objects of luminosity $\sim 10^{39}$ ergs/sec each).

In the absence of unambiguous data on the profile of the x-radiation measured near the plane or the intensity distribution for sources with $S \ll 2$ cts/sec, it is impossible to determine the nature of the unidentified high latitude sources. The two possibilities we have discussed are not only very different from each other, but also very different from previously catalogued sources. The local possibility has sources more than two orders of magnitude weaker than the usual

galactic x-ray objects, with an integrated luminosity which is not competitive with that from the stronger objects. The extragalactic possibility implies luminosities more than two orders of magnitude larger than the known cluster sources, and more than an order of magnitude larger than that from 3C 273, the most powerful emitter yet classified. Perhaps higher richness clusters at earlier epochs are the seats of such emission, but such an extension is not justified until the local alternative is demonstrated to be incompatible with the data.

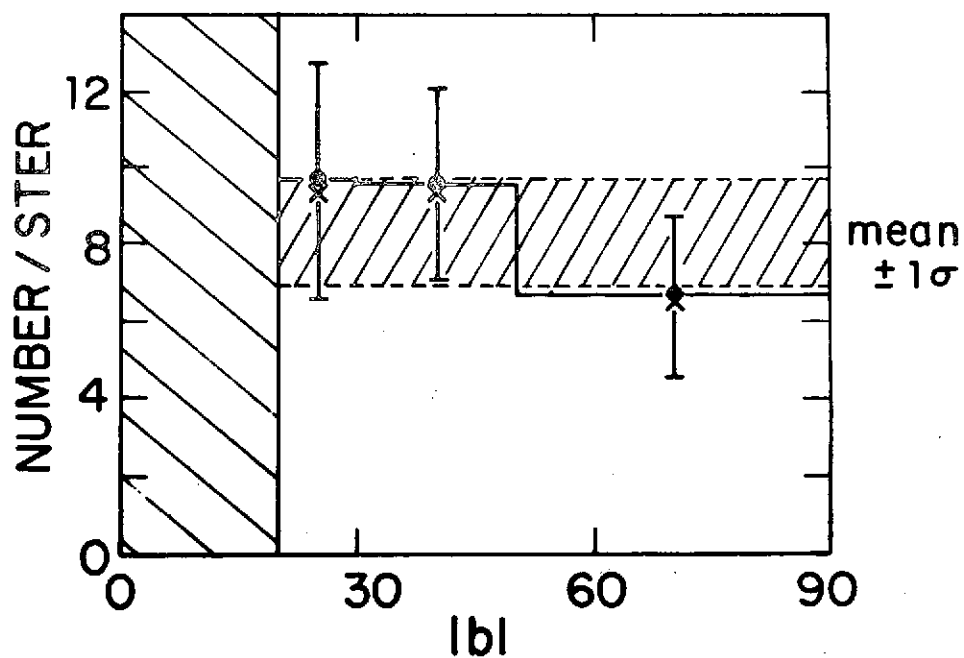
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FIGURE CAPTIONS

1. Latitude distribution of the unidentified high latitude sources. The error bars and $\pm 1\sigma$ range include both the source counting statistics and the sky coverage uncertainty.
2. High latitude source intensity distribution. The crosses in (a) refer to all sources (unidentified and identified), while the points with error bars are for those which are unidentified. The latter distribution is replotted differentially in (b), with the mean $\pm 1\sigma$ range defined from all data points excluding the highest intensity bin ($x < 0.1$).
3. Number of sources expected at $S \geq 2$ cts/sec with the fractional sky coverage of the UHURU catalog, as a function of κ and assumed source horizon. The $\pm 1\sigma$ range here refers only to the source counting statistics, and does not include the $\sim 20\%$ uncertainty in effective sky coverage.

(a) Latitude Distribution
of the Unidentified Sources



(b) Latitude Distribution
of the Unidentified Sources
($S < 4$ ct/sec)

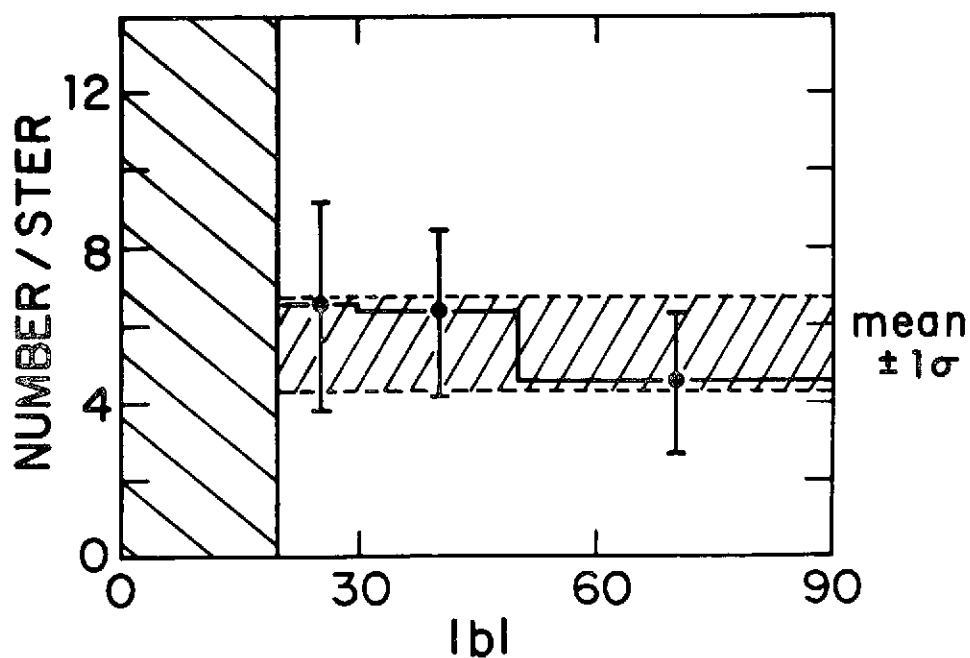


Fig. 1

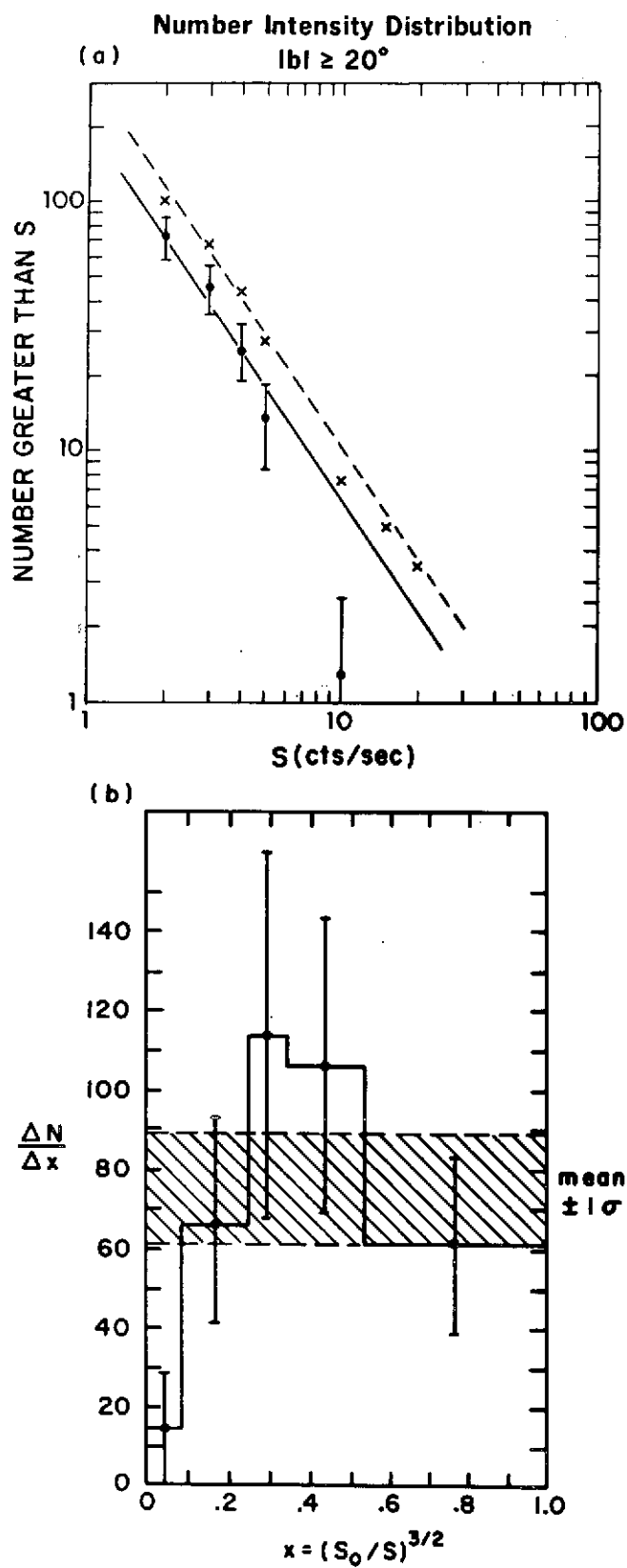


Fig. 2

