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HEAO 1 MEASUREMENTS OF THE GALACTIC RIDGE

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ABSTRACT

We have systematically searched the HEAO A2⁺ experiment data for unresolved galactic disc emission. Although there are suggestions of non-uniformities in the emission, our data are consistent with a disc of half-thickness 241 ± 22 pc and surface emissivity (2-10 keV) at galactic radius R(kpc) of $2.2\ 10^{-7} \exp(-R/3.5)$ erg/cm^2/s ($R > 7.8$ kpc), giving a luminosity of $\sim 4.4\ 10^{37}$ erg s^{-1}. If we extrapolate the model to radii less than 7.8 kpc, the unresolved disc emission is $\sim 1.4\ 10^{38}$ erg s^{-1} (2-10 keV) i.e. a few per cent of the luminosity of the galaxy in resolved sources. The disc emission has a spectrum which is significantly softer than that of the high galactic latitude diffuse X-ray background and it is most probably of discrete source origin.

⁺The HEAO A2 experiment is a collaborative effort led by E. Boldt of GSFC and G. Garmire of CIT with collaborators at GSFC, CIT, JPL and UCB.

Subject headings: galaxies: Milky Way - galaxies: structure - X-rays: sources

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I. INTRODUCTION

The A2 proportional counter experiment on HEAO 1 was designed to be particularly effective in searching for large scale features and anisotropies in the unresolved 2-50 keV X-ray sky. The satellite mission, launched Aug. 1977, was scanning in nature and in 6 months the whole sky was covered in a roughly uniform manner. We have isolated two unresolved galactic components in the data. The most prominent large scale feature is a galactic latitude dependence of the flux which can be seen at high latitudes, away from the confusion of the sources in the galactic plane (Iwan et al. 1981). A similar effect in the Ariel 5 data is reported by Warwick, Pye and Fabian (1980) and in the Uhuru data by Protheroe, Wolfendale and Wdowczyk (1980), although we believe it is likely that these authors modelled a composite of the two components we have now isolated.

The subject of this paper is our second component, which was found in a search for unresolved disc emission of a smaller scale height, such as would be consistent with a few earlier reports of disc enhancements in isolated directions. The first measurements, Cooke, Griffiths and Pounds (1969) and Hudson, Peterson and Schwartz (1971), were undoubtedly contaminated by now resolved discrete sources (see e.g. Cooke and Pounds 1971). However, Bleach et al. (1972) with a rocket-borne proportional counter experiment observed between longitudes of 57° and $65\overset{\circ}{.}5$, a direction in which the cross-section along spiral arms is small (Simonson 1976), and, despite no reported discrete sources along the line of sight, measured a significant 2-10 keV ridge excess. This was confirmed by Wheaton (1976) who, with the OSO 7 scintillators, extended the spectrum to 40 keV. At $\ell=240^\circ$ he reports a flux which is a factor of 2.5 lower than at $\ell=55^\circ$. At $\ell=140^\circ$ he did not achieve a positive ridge detection. We detect ridge emission in an ensemble of directions and present here the measurements and discuss likely origins for such a flux.

II. OBSERVATIONS

In HEAO 1's normal scanning mode the A2 experiment (Rothschild et al. 1979), with its look axis orthogonal to the satellite spin axis, described great sky circles at the rate of about one per 30 minutes. The spin axis pointed towards the sun, and thus moved by roughly a degree each day. In six months the whole sky was scanned. The angle, e, which a scan in ecliptic latitude made with the galactic plane varied gradually with spin axis direction. When the ecliptic scans cut the galactic plane at longitudes close to $\ell=105^0$ and $\ell=285^0$ the angle was near to 90^0 and so these directions are particularly well suited for searching for galactic disc emission. The smallest angle, which occurred when the galactic center and anti-center were in view, is $\sim 30^0$.

The data presented here are from our first complete sky coverage. We selected 120 directions in the galactic disc at zero latitude, beginning at 3 degrees longitude and incrementing by 3 degrees thereafter. For each direction in turn, data within 12.5 degrees along the scans were binned in 1/4-degree intervals and we constructed an average of scans taken over roughly four days. Longer portions of scan were not taken so that the expected flux variation over the scan due to the large scale galactic component, mentioned in the introduction, would be less than 10%.

The intention was to search for a ridge with a projected extent in the scan direction of $<$ 5 degrees half-angle. We used only the two detectors with a field of view of 1.5 degrees FWHM along the scan direction and 3 degrees FWHM perpendicular to the scan. The detector layer combination chosen for this analysis is defined by Marshall et al. (1979) and gives rates in units of

R15 counts/sec, covering the 2-50 keV energy range. Combined internal detector background and extragalactic diffuse sky flux give roughly 6-7.5 R15 counts/sec.

a. X-ray Ridge Intensity

We rejected those of our 120 25-degree scan averages containing either more than three known sources or any single source greater than 20 counts/sec. This eliminated scans centered around $|\ell| < 50^{\circ}$, the Vela and Cygnus directions, among several others. Directions within 50° of the galactic anticenter were also excluded since values for e are smallest here and we found we were not sensitive to the flux variations consistent with the results in other directions. We fit each ith averaged scan (from here on referred to as ith scan), of the 23 remaining, to a constant background and as many point sources, to a maximum of three, as required. We computed chi-squared for the best fit. We then assumed the galactic disc to be a diffuse X-ray emitter and tested for improvement in chi-squared.

The flux in the jth bin (of 100) of the ith scan (of 23) is given by:

$$I_{ij} = B_I + \iint \left(\frac{\int Q_{ij}(r,\theta)\, f_{ij}(r,\theta,\Gamma_1)\, dr}{4\pi} + \frac{B_D g_{ij}\,(\theta,\Gamma_2)}{4\pi} \right) d\theta\, d\phi$$

(1) B_I is the detector internal background flux which is constant but, due to an experiment reconfiguration during the first sky scan, is one of two values differing by about 40%. B_I is roughly 25-45% of the total flux.

(2) θ is the angle to the detector in the scan direction and takes values from zero to $\pm\, 1\overset{\circ}{.}5$.

(3) ϕ is the angle to the detector perpendicular to the scan direction and takes values from zero to $\pm\, 3^{\circ}$.

(4) $Q_{ij}\,(r,\theta)$, the emissivity of the unresolved disc emission at distance r,

is modified by the function f which accounts for flux absorption by neutral hydrogen along the line of sight. For spectral index $\Gamma_1 = 2.8$ (see next section), we find $f(r,\theta) \simeq \exp(-1.4\ 10^{-23}\ N_H(r,\theta))$.
We adopt a simple model for the gas in the galaxy, since more complexity is not warranted by the statistical accuracy of our data. We neglect molecular hydrogen, since it is mostly confined to radii < 8 kpc and all our 23 directions are at longitudes > 50^0. We assume that the gas uniformly fills a disc of half-thickness 120 pc (Baker and Burton 1975) and that $N_H = 0.35r$ atoms cm^{-2}.

(5) B_D is the isotropic background intensity, modified by the function g to account for absorption. The background is represented by a 40 keV thermal bremsstrahlung spectrum (Marshall et al. 1980), for which absorption by neutral hydrogen is given by:

$$g(r,\theta) \simeq \exp(-6.3\ 10^{-24}\ N_H(r,\theta))$$

N_H is modelled as above. Since the scans cross the galactic plane at relatively large values of θ, we neglect the small dependance of Q, f and g on ϕ.

As the simplest model, we first adopted a uniformly emitting flat slab of radius R_{max} and half-thickness $Z_{1/2\ max}$.

$$\begin{aligned} Q_{ij}(r,\theta) &= Q(R,Z_{1/2}) \\ &= \text{constant},\ q_i \text{ if } R < R_{max\ i} \\ &\qquad\qquad\qquad Z < Z_{1/2\ max\ i} \\ &= 0 \text{ otherwise.} \end{aligned}$$

Our sensitivity to R_{max} is small since our information about emission at distances $\gtrsim 8$ kpc from the sun is limited. We adopt $R_{max} = 16$ kpc and a galactic center to sun distance of 10 kpc.

We tested each of our 23 directions in turn and found improvement in chi-squared, from the fits without a ridge, in 14 of the 23 directions (Fig. 1). Upper limits to q_i were found for the other 9. The values of q_i (Fig. 2) are clearly inconsistent with the hypothesis that q_i = constant. $Z_{1/2\ max\ i}$ = constant = 319 pc is an acceptable fit, implying that our sensitivity to the scale height parameter is lower.

As a second model we adopted a radial emissivity decrease:

$$\begin{aligned} Q_{ij}(r,\theta) &= q_i \exp(-R/R_i) \text{ if } Z < Z_{1/2\ max\ i} \\ &= 0 \text{ otherwise.} \end{aligned}$$

We tested our 23 directions for consistency with R_i = constant, q_i = constant. Our best fit was $R_i = 3.5$ kpc. The best value for z_{max} was now lower since this model places the flux contributions closer to the sun on average. We found $Z_{1/2\ max\ i}$ = constant = 241 pc. Details of the fits in the 23 directions are given in Table 1. Table 2 summarizes the results for the two models tested. We notice that the radial-dependent emissivity model gives a greatly improved chi-squared over the case of uniform emissivity. The chi-squared is acceptable when an 18% error to the model dependent galactic absorption correction to the diffuse background counts is added to the statistical errors in the count rates. Figure 3 shows the radial dependence in the range we have investigated and, for comparison, distributions of total mass, neutral hydrogen and > 100 MeV gamma-rays, which each fall off in a similar manner.

In both of these models we assumed that the sources were either diffuse or of low enough luminosity that only a small part of the disc contributes resolved rather than unresolved emission. We show below that this assumption should not greatly affect our results concerning the assessment of possible discrete source contributions.

b. Spectrum

We use the two scalers in layer 1 and two in layer 2 of each of the two detectors with $3^0 \times 1.5^0$ fields of view to construct 8 independent energy windows for examining the spectrum. The energy response of the windows overlaps and is mainly in the 2-15 keV band. For only 3 directions are the flux measurements of high enough statistical significance for spectral fits to be attempted. Figures 4(a) and (b) show the spectral fits to the data before correction for absorption of the diffuse background, assuming power law and thermal bremsstrahlung spectral forms respectively. These represent upper bounds to the power law hardness and temperature. Figures 4(c) and (d) are the fits after the correction has been made. After the absorption correction, we see that the column densities we derive are roughly as expected, i.e. the average column density between us and all points along the line of sight. The spectra are very soft relative to that of the diffuse background (Marshall et al. 1980) and slightly softer than that found by Iwan et al. (1981) for the more extended unresolved galactic component. Our ridge detection is not significant above 15 keV.

III. DISCUSSION

Although the emissivity distribution of the unresolved 2-10 keV X-ray component is probably not completely smooth (we have only upper limits in some directions), within our statistics it can be modelled as a disc, best fit if the emissivity has a small radial dependence. This radial dependence is not unlike that exhibited by the total mass, neutral hydrogen and > 100 MeV gamma-rays of the galaxy (Fig. 3). We note, however, that our scale height is larger than for population I objects and tracers thereof, such as molecular hydrogen clouds, and ~ 2 times that for neutral atomic hydrogen. The total 2-10 keV galactic luminosity in this unresolved component is a few per-cent of that of known resolved galactic X-ray sources.

We can compare with the work of Bleach et al. (1972) and Wheaton (1976) at 10 keV, an energy which is in the range of each experiment and at which the photons are little affected by galactic absorption. At a longitude of ~ 60°, our flux of (6±1.6) 10^{-2} $cm^{-2}s^{-1}sr^{-1}keV^{-1}$ agrees with Bleach et al. ((6±2.5) 10^{-2} $cm^{-2}s^{-1}sr^{-1}keV^{-1}$). Wheaton's 55° longitude flux ((3.7±1.3) 10^{-2} $cm^{-2}s^{-1}keV^{-1}$) is lower than ours ((8±2) 10^{-2} $cm^{-2}s^{-1}sr^{-1}keV^{-1}$), but since he reports flux from a disc which is 1.5-2.5 times thicker, there is agreement in total ridge excess. Bleach et al. measured a spectral index of 2.8±0.5 (2-10 keV), which agrees well with the present work. Wheaton's value of 1.6±0.3 (10-40 keV) implies a flattening of the spectrum above 10 keV. Any direct comparison of average emissivity depends on the scale height attributed to the disc, more poorly determined in the previous experiments. Our 10 keV emissivity is a factor of ~ 1.5 higher than that given by Wheaton and comparable with that of Bleach et al.. We now consider some possible origins for the disc radiation.

1. Discrete Sources

We emphasize that our measurements do not directly tell us of emission at galactic radii $R < 7.8$ kpc. Furthermore, our information about emission at distances $\gtrsim 8$ kpc from the sun in any direction is limited.

For simplicity, assuming uniform emissivity, if the surface density of sources is n pc^{-2} and the average 2-10 keV luminosity is L erg/s,

$$L\eta = 1.2\ 10^{29}\ \text{erg/s/pc}^2 \qquad (1)$$

A single source would exceed the intensity of the ridge and would thus be clearly resolved if brighter than ~ 1 R15 ct/s and thus closer than d_1 where

$$d_1 \simeq 1.8\ 10^{-14}\sqrt{L}\ \text{pc} \qquad (2)$$

For each fit summed scan, data are from about a 6 degree longitude range. Since a minimum of 3 sources must be contributing, each direction must satisfy.

$$\int_{d_1}^{d_2} 0.105\ r\ \eta\ dr > 3 \qquad (3)$$

where 0.105 (radians) is the detector field of view perpendicular to the scan path. Since directions with $d_2 \leq 8$ kpc must satisfy (3), we can solve to find

$$\eta > 1.4\ 10^{-6}\ \text{pc}^{-2}; \qquad L < 9.0\ 10^{34}\ \text{erg/s}.$$

We can further restrict the luminosity by calculating the number of sources we would expect to resolve at high galactic latitudes. We assume a simple luminosity function:

$$\begin{aligned} f(L) &= A\ L^{-1} \qquad L_{min} < L < 10^2\ L_{min} \\ &= 0 \text{ otherwise} \end{aligned}$$

For the galactic absorption correction we adopt the approximate hydrogen density distribution given in section II(a). For populations of $\mathcal{L}$, we have computed the number of high and low galactic latitude sources we would resolve at various flux thresholds, assuming the population to be entirely responsible for our ridge emissivity using its best fit exponential radial fall-off. Figure 5 shows the results for a flux threshold of 5 Uhuru ct/s. This unit is adopted to ease direct comparison with the Uhuru X-ray catalog (Forman et al. 1978). The number of resolved sources increases with $\mathcal{L}$ at low values ($N \propto \mathcal{L}^{1/2}$ is expected for a spherical source distribution with no galactic absorption). For the high galactic latitude sources there is a maximum N such that subsequent increases in luminosity, and thus source horizon, give no net gain in N since the limit of the disc (slightly smaller than its geometric size due to absorption effects) has been reached. We may have underestimated N for $\mathcal{L} > 5\ 10^{34}$ erg/s. At this high a luminosity the source horizon is large enough that our diffuse ridge models are inapplicable and our fitting has underestimated the scale height and the source density.

All sources > 5 Uhuru ct/s at $|b| > 20^{\circ}$ are identified (see summary of Piccinotti et al. 1981). Of the 6 of galactic origin, Sco X1, Her X1 and two globular cluster sources are members of populations which are too luminous to account for the unresolved ridge. Only two, EX Hydrae and AM Her, both lying close to the lower threshold, are members of classes of potential interest and are discussed below. With 95% confidence we can therefore exclude populations from luminosity ranges for which we would predict more than ~ 6.3 resolved sources i.e. $1.5\ 10^{32}$ - $4\ 10^{33}$ erg/s (Figure 5). We are left with permitted luminosity ranges of $4\ 10^{33}$ - $9\ 10^{34}$ erg/s and $< 1.5\ 10^{32}$ erg/s.

As can be seen from Figure 5, if the higher luminosity sources (in the range $4\ 10^{33}$ - $9\ 10^{34}$ erg/s) are significant contributors to the ridge, there should be a substantial number of resolved low latitude sources of strength >

5 Uhuru ct/s. Matilsky (1977) concluded that such a population of X-ray sources exists based upon the fact that the 5-50 Uhuru ct/s $|b| < 20^o$ sources from the 3U catalogue exhibit a larger dispersion in galactic latitude than the higher intensity ones. Rothenflug, Rocchia and Casse (1979) achieved the latitude dispersion without invoking close medium luminosity sources by assuming runaway systems for which the scale-height increases with distance from the galactic center. However, in discussing the galactic ridge flux of Bleach et al. (1972), they concluded that a medium luminosity population could be accommodated within the statistics of observed sources, but it would be in excess of a smooth continuation of the luminosity distribution for more luminous sources. Protheroe and Wolfendale (1980a) noted that the longitudinal distribution of the weakest low latitude Uhuru sources is evidence for a medium luminosity population.

Since these reports, several more of the Uhuru sources have been identified. From the 5-50 Uhuru ct/s sources in the revised 4U catalogue (Forman et al. 1978), candidates for a population of $4\ 10^{33}$ - $9\ 10^{34}$ erg/s now number ~ 5 for $60 < \ell < 300$ and ~ 16 for $|\ell| < 60$ (c.f. Matilsky's 20 and 27). Although the ridge is consistent with giving 40-100% of the sources in the range $|\ell| < 60^o$, it predicts an excessive number for $60 < \ell < 300$ such that agreement with the observations is only .8% ($9\ 10^{34}$ erg/s population) or 5% ($4\ 10^{33}$ erg/s population) probable. It is more likely that $\lesssim$ 50% of the ridge is due to a medium luminosity source population.

Candidates for both the permitted luminosity ranges are known. None clearly stands out as the obviously responsible population and several could well contribute a significant percentage of the ridge flux. We discuss briefly here whether or not they could produce the observed characteristics.

(a) Medium Luminosity Binary Systems

Mushotzky et al. (1977) suggested that binary systems containing Be stars could contribute the ridge emission of Wheaton (1976). Some members of this class have 2-10 keV luminosities of a few times 10^{33} erg s^{-1} (X Per and γ Cas), others in excess of 10^{35} erg s^{-1} (HEN 715, WRA 977 and GX 304-1) (see Bradt, Doxsey and Jernigan 1979). The scale height of B stars is only ~ 60 pc (Allen 1973), but, as Rothenflug, Rocchia and Casse (1979) point out, runaway velocities from a supernova producing a neutron star could broaden the distribution by the time those systems become X-ray sources of this luminosity.

Neutron star binaries with normal companions of lower mass than Be stars could also contribute (Ogelman and Swank 1974). The pulsars among these have spectra significantly harder than that we deduce for the ridge, but the spectrum could depend on the luminosity.

The luminosity range 10^{34} - 10^{35} erg/s is possible for white dwarf binaries (Kylafis and Lamb 1979). No such candidates have been firmly identified but no reason is presently known why candidates should not evolve. The temperature we observe is about that which Kylafis and Lamb predict for such sources.

(b) Lower Luminosity White Dwarf Binary Systems

We exclude AM Her-type objects as a major contributor on the basis of the X-ray spectrum. A flat spectrum, similar to that of the high latitude diffuse background, was found for AM Her by Swank et al. (1977) and 0311-227 by White (1981).

In the 2-10 keV range the brightest dwarf novae have luminosities up to a few times 10^{32} erg s^{-1}. Although variable, the spectra tend to fit thermal bremsstrahlung forms with kT ~ 5-20 keV (Swank et al. 1978a, 1978b). If the mean luminosity of sources is ~ 2 10^{31} erg s^{-1}, a space density of ~ 10^{-5}

pc^{-3} is required for a substantial contribution to the ridge. Taking there to be a few within ~ 100 pc of the sun, the density could be a few times 10^{-6} pc^{-3}, and thus at this time we cannot reject the class as a potentially large contributor.

(c) RS CVn Systems

RS CVn systems have recently been found to emit at two temperatures, ~ 6 10^6 K and ~ 50 10^6 K, with roughly equal energy in each component; 10^{30}-10^{31} erg s^{-1} at 0.4-4 keV (Swank and White 1980; Swank et al. 1981). For a thermal bremsstrahlung spectrum of 50 10^6 K, the 2-10 keV luminosity is a factor of 2 below that for 0.4-4 keV. RS CVn systems are estimated to have a space density of about 10^{-5} pc^{-3} (Walter, Charles and Bowyer 1978) although a scale height of only about 110 pc. At a mean 2-10 keV luminosity of 5 10^{30} erg s^{-1}, they could contribute 8-27% of the ridge.

(d) Other Stars

Our scale height is compatible with the X-rays originating from stars of type later than about F (Allen 1973). Although all types of stars are X-ray emitters in the energy range ~ 0.2-3 keV (Vaiana et al. 1981), contributions to the ridge remain uncertain until it is known whether or not coronal emission of a temperature of about 50 10^6 K, as seen in the RS CVn systems, is a common feature of late stars. Temperatures measured for early-type stars are below 5 10^6 K (Cassinelli et al. 1981).

Thus, present estimates of the densities of RS CVn stars and cataclysmic variables make each sum likely to contribute ~ 15% of the ridge and comparable amounts might come from even lower luminosity late-type stars. That appears to leave a majority of the deduced ridge emission still unaccounted for and so these categories do not challenge previous suggestions of a population with luminosity ~ 10^{34} erg s^{-1} (possibly including sources mentioned in (a) above). However, a large sample of these sources should be among the known resolved sources and the number so far identified places a likely limit on the ridge contribution of $\lesssim$ 50%.

In Figure 6 we show the contribution which a population entirely responsible for the ridge would make to the observed number of resolved Uhuru sources given by Matilsky (1977) for our exponential radially-dependent best fit ridge parameters. For a population in the higher luminosity range the log N - log S curve should steepen below ~ 1 Uhuru ct/s although at slightly lower count rates the sources become resolved throughout the galaxy and the curve should become flat. If, on the other hand, very low luminosity sources are responsible for the ridge, the steepening should be more pronounced, but not until below 0.2 ct/s. We have also estimated the effect these populations should have for the IPC on the Einstein Observatory. We assume an extrapolation of our derived spectrum into the energy range of the Einstein Observatory (0.1-4.5 keV). (Note that the galactic gas (modelled as given in Section IIa) has a greater effect in reducing the count rate than for the Uhuru energy range). Figure 6 shows the average source density for 80 sq.deg. regions towards the galactic center and anticenter. We infer that sources of the higher luminosity should show up in typical 2000 sec IPC exposures ($s_{min} \approx 3\ 10^{-2}$ ct/s) towards the galactic center at a density of a few per square degree, whereas 40,000 sec exposures ($s_{min} \approx 2\ 10^{-3}$ ct/s) towards the anticenter should reveal sources of the lower luminosity at a similar density.

2. Diffuse Emission

(a) Hot Gas

Figure 4(d) shows that our spectral results are consistent with thermal emission from a hot gas in the range 1-7 10^7 K. Evidence for a hot component of gas in the interstellar medium has come from ultraviolet O VI lines and diffuse soft X-ray emission below 2 keV (see review of McCray and Snow 1979). Various temperatures have been suggested for the gas, usually ranging between 10^5 and 5 10^6 K, with some evidence for real spatial variations. For the temperature and emissivity we deduce, distributed hot gas would have too high a pressure ($\sim$ 4 10^4 cm^{-3} K) to be in pressure equilibrium with the cooler gases (Cox and Smith 1974). Maintenance of as much 3 10^7 K gas as 10^6 K gas seems unlikely. Young supernovae remnants ($\lesssim$ 20 pc in diameter) can have $\sim$ 10^{35} erg s^{-1} luminosity at 3 10^7 K, but the identified radio sample is thought complete (Clark and Caswell 1976) and there would not be enough to contribute significantly.

(b) Inverse Compton Emission

2-10 keV X-rays can be produced by inverse compton scattering of the microwave background on cosmic ray electrons and positrons which have energies of a few GeV (see e.g. Ginzburg and Syrovatskii 1964; Blumenthal and Gould 1970).

The local electron density at these energies can be measured directly, but the scale height of the electrons depends on how quickly they propagate after crossing the disc boundary. If the propagation is slow, they could lose a large proportion of their energy in a region local enough to the disc to fit the sometimes-used description of "galactic halo". Interpretations of high latitude radio data (Strong 1977) and gamma-ray measurements (see Stecker 1979) suggest that there is probably not a drastic decrease in electron density beyond the disc boundary and that they have a scale height of a few kpc. Such interpretations are however highly model dependent. Warwick, Pye and Fabian (1980) calculate a local X-ray emissivity of 8 10^{-31} erg $cm^{-3}s^{-1}$

(2-10 keV) with an uncertainty of a factor of a few. Since the scale height of their unresolved X-ray disc is undetermined, their data support an emissivity this low, within errors. However, the discrepancy with our measurements is a factor of 8-11. The unlikelihood that the emission has the required scale height and the fact that the predicted X-ray spectral slope ($\Gamma \approx 1.9$) is harder than measured are further reasons for rejecting this as the dominant emission process.

The contribution from inverse Compton scattering of starlight on the cosmic ray electrons and positrons is open to more uncertainty since the local density of cosmic rays in the relevant 15-40 MeV energy range cannot be inferred without the model-dependent solar modulation correction to observations. Electrons of these energies lose energy mainly by ionization in a lifetime of $2\ 10^6$ - $2\ 10^7$ years (see e.g. Ginzburg and Syrovatskii 1964 for relevant formulae) and their scale height is thus probably compatible with that of the X-ray ridge. An electron spectrum $j(E_e) = A\ E_e^{-m}\ cm^{-2}s^{-1}sr^{-1}eV^{-1}$ will produce an X-ray emissivity $q(E) \propto E^{-(m+1)/2}cm^{-3}s^{-1}eV^{-1}$. Since our data require $(m+1)/2 = 2.8$, the electrons must have a very steep index; $m = 4.6$. The production is well within the Thomson regime and we use the formulae given in Ginzburg and Syrovatskii (1964) to find that in order to satisfy our 2-10 keV local X-ray volume emissivity, $j(E_e) = 1.8\ 10^{29}\ E_e^{-4.6}cm^{-2}s^{-1}sr^{-1}eV^{-1}$. We have assumed a local starlight energy density of 0.44 eV cm^{-3} and a mean photon energy of 1.4 eV. If we relax the spectral index constraints slightly to allow $m = 3.8$, we find $j(E_e) \approx 2.4\ 10^{23}\ E_e^{-3.8}\ cm^{-2}s^{-1}sr^{-1}eV^{-1}$. In the 10-30 MeV range these fluxes are about five orders of magnitude above the electron observations at earth, after solar modulation has played a role (see summary of Ramaty 1974). The values are also two orders of magnitude above both the extrapolation of the fluxes determined above ~ 100 MeV by Webber, Simpson and Cane (1980), from an analysis of non-thermal radio data in the galactic disc, and also their estimated range for the 10-100 MeV band using solar modulation theory. There is currently no reason to think that an electron component of the required steep spectrum and intensity exists.

We note that inverse Compton scattering of far-infrared radiation at about 0.012 eV on electrons of energy 200-400 MeV can also produce 2-10 keV X-rays. Using the 200-400 MeV flux of Webber, Simpson and Cane (1980), the predicted far-infrared-produced flux is only 0.1% of our observations, even allowing for a local photon energy density as large as for starlight.

(c) Synchrotron Radiation

Synchrotron emission is the mechanism favored by Protheroe, Wolfendale and Wdowczyk (1980) to interpret the Uhuru high latitude variation. Bleach et al. (1972) and Warwick, Pye and Fabian (1980) both pointed out that synchrotron radiation could provide a sufficient emissivity if the electron spectrum continued to sufficiently high energy and that too little is known about the electron spectrum to rule this out. We can, however, consider the energy requirements and the significance of a contribution from this mechanism.

Assuming a magnetic field of 3 10^{-6} Gauss, electrons of about 10^{14} eV are required to produce the X-rays. The lifetime of such particles to synchrotron radiation is therefore $t \approx 10^4$ years. Cosmic rays of rigidity > 7.6 GV exhibit an energy dependent path length in the galactic disc before escape to a region from which they cannot return to the solar system vicinity. Assuming electrons travel by diffusion, the energy dependence in the diffusion coefficient is roughly $D = D_0(E_e/7.6)^{0.4}$ for $E_e > 7.6$ GeV (Ormes and Freier 1978). Combining results of Stecker and Jones (1977) and Jones (1979), $D_0 \lesssim 6\ 10^{27}$ cm^2s^{-1}. This implies that electrons of 10^{14} eV will travel $\sim \sqrt{3Dt} < 170$

pc in their lifetime. The particles can therefore be expected to fill a disc extended by a few hundred parsecs from that of their sources. Considering the uncertainties in D and the nature of the sources, a volume comparable with our X-ray disc would not seem unreasonable.

We can calculate the required rate of energy injection into the electrons. For X-rays of energy E from electrons of energy E_e, $E = b\ E_e^2$, where $b = 6.62\ 10^{-20}\ H(\mathrm{Gauss})$. For an injection,

$j(E_e) = k\ E_e^{-m}\ s^{-1}\ eV^{-1}$

and total energy loss by synchrotron radiation, the galaxy emission is,

$$Q_s(E) = \frac{1}{E\ 2\sqrt{bE}} \int_{\sqrt{E/b}}^{\infty} j(E_e)dE_e\ s^{-1}eV^{-1} \qquad (4)$$

(e.g. Wolfendale and Worrall 1977).

The local electron spectrum from a few GeV out to its highest measured energies (~ 10^3 GeV) exhibits a spectral index of ~ 2.7 (e.g. Muller and Meyer 1973). The degree to which this index is that of the injection spectrum depends on the electron propagation. If the electrons depart quickly from the vicinity of the disc after a containment time of 10^6 - 10^7 yrs (likely times for nuclear cosmic rays) then, since up to a few tens of GeV the energy losses will be negligible, the injection spectrum will have the same index, i.e. $m \simeq 2.7$. If, however, the electrons remain longer in a "galactic halo", then the ambient spectrum will reflect energy losses and thus be steeper than the injection spectrum. Support for this interpretation was presented in the previous section. Protheroe and Wolfendale (1980b) conclude that an injection index of m = 2.2 gives the best agreement with a variety of astrophysical observations. This would imply an X-ray index of 2.1 which may not be inconsistent with our data if we allow a 3 sigma error margin. Since $Q(E) \propto b^{(m-2)/2}$, we see that the dependence on H is extremely weak. Assuming $H = 3\ 10^{-6}$ Gauss and fitting the local X-ray emissivity we find $j(E_e) = 10^{53}$ $E_e^{-2.2}$ s^{-1} eV^{-1}. If this injection spectrum is extrapolated to 10 MeV, the energy rate is 10^{48} erg yr^{-1}. If, for example, the energy for particle acceleration is supplied by supernovae at a rate of one per 30 years (Higdon and Lingenfelter 1980), this would require $3E_{51}$% of a supernova's energy, where E_{51} is its total energy in units of 10^{51} ergs. Although the mechanism of Blandford and Ostriker (1978) will allow 10^{50} ergs per supernova to accelerate protons, our requirements are perhaps uncomfortably high. We expect the energy injected into protons to be at least as high as that into the electron component. If the injection spectra of electrons and protons are both roughly power laws in kinetic energy down to mildly non-relativistic energies, then they share roughly equal total energy density. Extending the electron spectrum down to non-relativistic energies, rather than cutting it off at 10 MeV, roughly doubles its required energy input.

There is however a further consequence. We stated that for this model the electrons of a few GeV in energy must be losing energy in the "galactic halo". Since the majority of this energy will be lost via inverse Compton scattering of the microwave background, we can use expression (4) above, with $b \approx 3.4\ 10^{-15}$, to find a 2-10 keV X-ray luminosity of $1.6\ 10^{39}$ erg s^{-1}. This is a factor of ~ 4 higher than the luminosity in the more extended (~ 3 kpc scale-height) unresolved galactic X-ray component (Iwan et al. 1981).

The model with $m = 2.7$ can also be rejected since the energy requirement of ~ 10^{48} erg yr^{-1} is increased to ~ $7\ 10^{50}$ erg yr^{-1}.

IV. CONCLUSIONS

HEAO-1 A2 experiment scans through the galactic plane exhibit ridges of enhanced unresolved X-ray emission in a number of longitude directions. The data are treated in a systematic way and found to be consistent with a model of emission from a disc, aligned with the conventional galactic disc. The fluxes in various directions can be best fit to a model in which X-ray emissivity (2-10 keV) has a dependence on galactic radius. Although the derived dependence is reasonably strong, our data only relate to radii > 7.8 kpc. We find a disc half-thickness of ~ 241 pc.

It is unlikely that our emission is predominantly from any of the considered diffuse processes. The contribution from synchrotron radiation is probably the most uncertain since the density of high energy ($\sim 10^{14}$ eV) electrons is highly model dependent. However, we have argued for a contribution of less than 25% since a consequence is the requirement for electrons of a few GeV being trapped in an extended "galactic halo" and there is already a limit to the electron density in such a halo from the X-rays produced by inverse Compton scattering of the microwave background radiation.

It is likely that our observed flux is of discrete source origin. The 2-10 keV X-ray luminosity of any dominant population must be $< 1.5\ 10^{32}$ erg s^{-1} or $4\ 10^{33}$ - $9\ 10^{34}$ erg s^{-1}. Several types of discrete sources may contribute competitively, notably RS CVn binaries, dwarf novae and other neutron star and/or white dwarf binaries not yet well classified. A log N - log S curve for sources with X-ray fluxes 10^{-14} - 10^{-10} erg cm^{-2} s^{-1} would constrain the relative contributions of these sources.

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TABLE 1

DERIVED EMISSIVITIES FOR THE 23 DIRECTIONS

a	b	c	d	e	f	g	h
51	20.3	33	2/1/0	353/95	144/94	9.8 ± 0.4	245 ± 29
54 *+	19.7	33	3/0/0	128/93	100/96	10.0 ± 0.5	268 ± 34
57	19.1	44	1/1/1	309/97	122/94	11.7 ± 0.8	116 ± 29
60	18.5	44	1/3/1	355/97	143/90	7.6 ± 0.6	225 ± 49
63	17.8	44	2/2/2	320/95	148/92	7.6 ± 0.5	388 ± 54
84 *	13.6	69	3/3/3	99/93	-	< 9.3	-
93 *	12.0	86	3/3/3	213/93	108/90	7.2 ± 0.6	219 ± 52
96 *	11.5	89	3/3/2	150/93	110/90	7.6 ± 0.6	203 ± 52
102 *	10.6	79	3/3/3	96/93	85/90	3.5 ± 0.8	303 ± 173
105 *+	10.2	75	1/1/1	139/97	97/94	5.6 ± 0.6	275 ± 86
108	9.8	72	3/3/3	131/93	121/90	4.8 ± 0.8	354 ± 164
117 *	8.7	58	2/2/2	103/95	-	< 5.8	-
129 *	7.7	46	3/3/3	104/93	-	< 3.9	-
237 *	8.2	43	3/3/2	112/93	90/90	5.1 ± 1.4	320 ± 147
243	8.7	44	2/1/1	133/95	-	< 5.5	-
246	9.1	49	0/0/0	131/99	-	< 4.0	-
249 *	9.4	51	0/0/0	117/99	-	< 3.1	-
252 *	9.8	53	2/2/0	117/95	-	< 3.1	-
255 *	10.2	57	1/1/1	108/97	-	< 3.1	-
258	10.6	61	1/1/1	136/97	-	< 2.8	-
276	13.6	89	1/1/1	156/97	129/94	4.5 ± 0.6	170 ± 78

279	*+	14.1	85	1/1/1	126/97	83/94	5.3 ± 0.6	193 ± 65
282		14.7	79	2/2/2	150/95	137/92	3.5 ± 0.7	408 ± 171

Column a: Galactic longitude in degrees

b: Line of sight, r(kpc), for disc radius R=16 kpc and sun-galactic center distance of 10 kpc

c: Angle between ecliptic scan direction and galactic disc, e, in degrees

d: Number of fit sources; without ridge/with ridge/number of required known sources. (Fit sources are allowed to exceed known sources if this results in an improved chi-squared)

e: Chi-squared/degrees of freedom; no ridge

f: Chi-squared/degrees of freedom; with ridge, assuming exponential radial emissivity model. (Only directions in which chi-squared improved when ridge added).

g: Average emissivity for line of sight in uniform emissivity model (erg/cm^3/s x 10^{30}). Upper limits are 2 sigma.

h: $z_{1/2}$ (pc) for exponential radial emissivity model.

*Final chi-squared acceptable at 95% probability level.

+Spectral parameters obtained.

TABLE 2

BEST FIT MODEL PARAMETERS

A: UNIFORM EMISSIVITY

$z_{1/2}$ = 319 ± 22 pc. Reduced chi-squared=0.6: Degrees of freedom=6: Acceptable.

$q=6.9\ 10^{-30}$ erg $cm^{-3}s^{-1}$. Reduced chi-squared=13; Degrees of freedom=22: Unacceptabl

$q_s(R=10\ kpc) = 1.3\ 10^{-8}$ erg $cm^{-2}\ s^{-1}$

L_x (extrapolated to include all the disc) = $9.4\ 10^{37}$ erg s^{-1}

B: RADIAL DEPENDENCE OF EMISSIVITY (R > 7.8 kpc measured)

$z_{1/2}$ = 241 ± 22 pc Reduced chi-squared=0.4; Degrees of freedom=6: Acceptable.

$q=1.5\ 10^{-28}$ exp(-R(kpc)/3.5) erg $cm^{-3}s^{-1}$. Reduced chi-squared=4.6; Degrees of freedom=21; Reduced chi-squared acceptable when an 18% error to the model dependent diffuse background counts is included

$q_s(R=10\ kpc) = 1.2\ 10^{-8}$ erg $cm^{-2}\ s^{-1}$

L_x (observed) = $4.4\ 10^{37}$ erg s^{-1}

L_x (including extrapolation within 7.8 kpc) = $1.4\ 10^{38}$ erg s^{-1}

95% probability range for q: ($9.7\ 10^{-29}$ exp(-R/4.1) - $2.4\ 10^{-28}$ exp(-R/3.0)) erg $cm^{-3}s^{-1}$

FIGURE CAPTIONS

Figure 1 - R15 count rates for accumulated scan segments, each centered at galactic latutide $b=0^o$, for 14 different longitudes. The data are in 1/4-degree bins. The response to a point source is triangular. The solid line shows the fit to the model which includes ridge emission, giving a χ^2 improved by $\Delta\chi^2$ over the model of constant flux plus $\leqslant 3$ discrete sources. Absorption of the diffuse background is particularly evident in directions such as $\ell=54^o$ and $\ell=105^o$.

Figure 2 - Average volume emissivities along the 23 directions for uniform emissivity model. Also shown is the average half-thickness of the disc for the 14 directions for which we have a positive detection of the ridge. Solid data points are those for which the final χ^2 was acceptable: Their mean value is 319 pc.

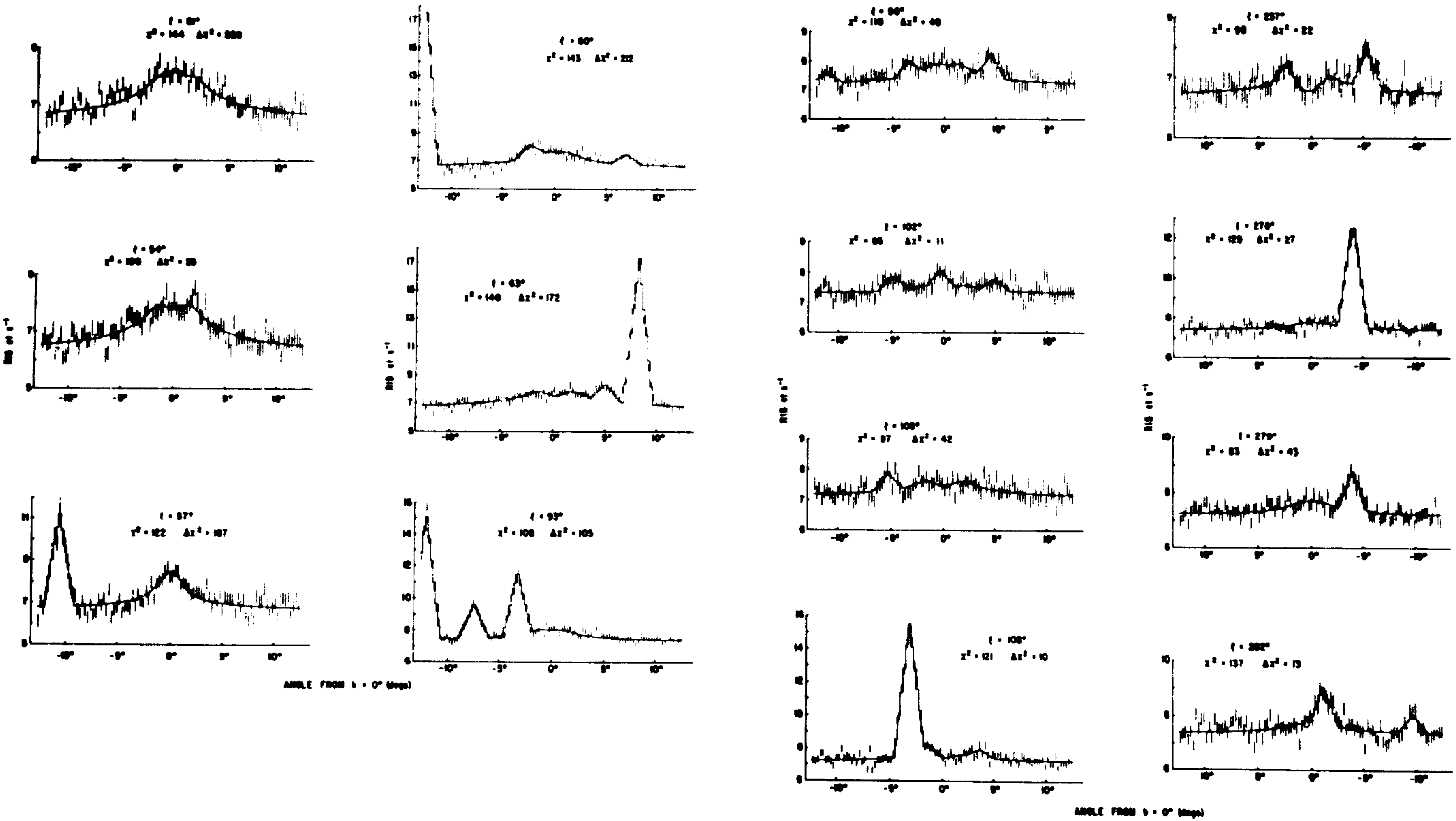
Figure 3 - The 95% probability range for the X-ray ridge volume emissivity as a function of galactic radial distance. The dashed lines are an extrapolation to radii not investigated by the present analysis. For comparison, the galactic radial distributions of total mass (Innanen 1973), neutral hydrogen (Burton 1976) and SAS II > 100 MeV gamma-rays (Strong and Worrall 1976) are also shown. The 14 determinations of the disc half-thickness for the radial emissivity model, for the directions for which we have positive ridge detections, are also shown. Solid data points are those for which the final χ^2 was acceptable: Their mean value is 241 pc.

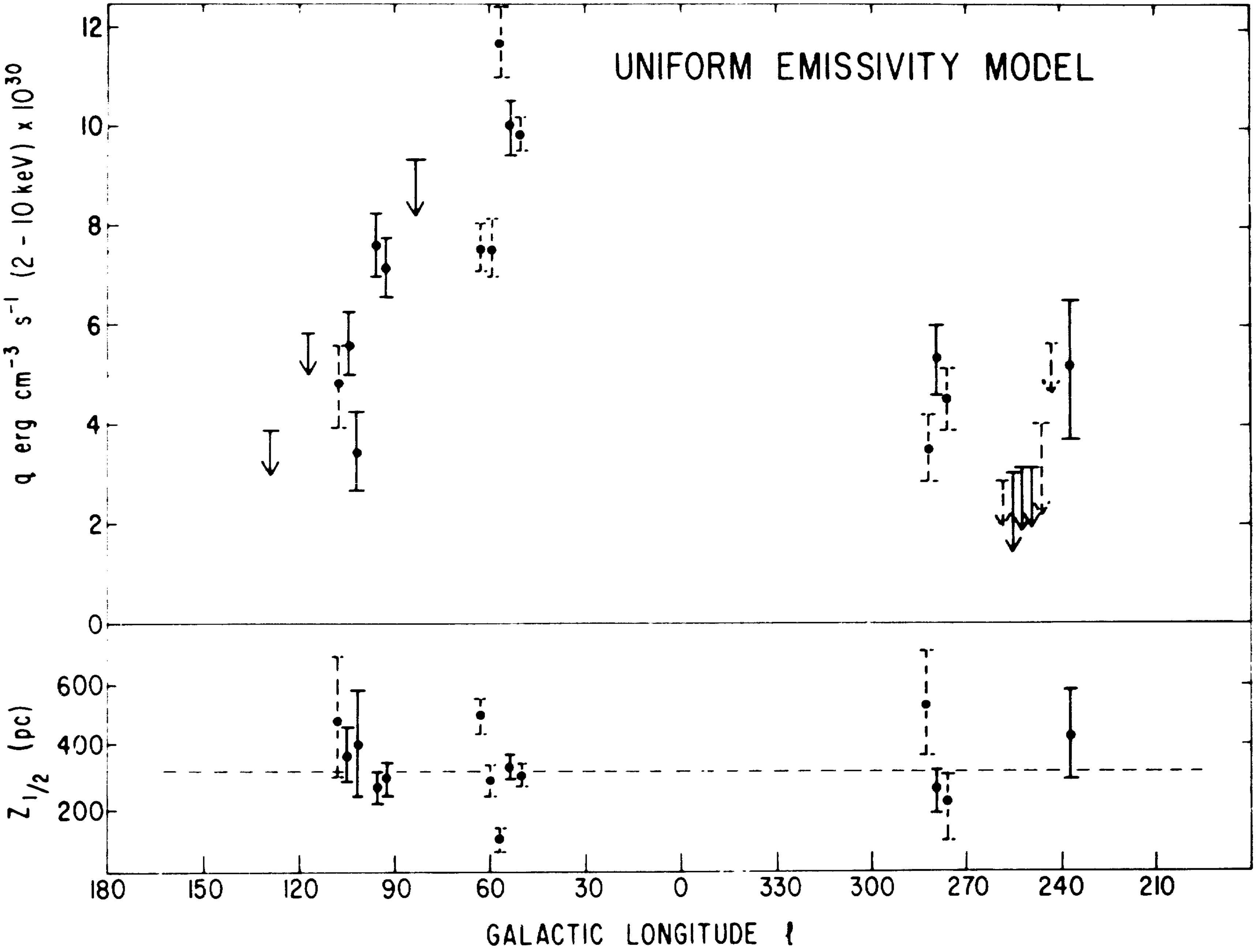
Figure 4 - 70% joint confidence limits on the spectral parameters for fits to power law and thermal bremsstrahlung models for the observed flux in three directions ((a) and (b)), and the flux after correction for absorption of the diffuse background ((c) and (d)).

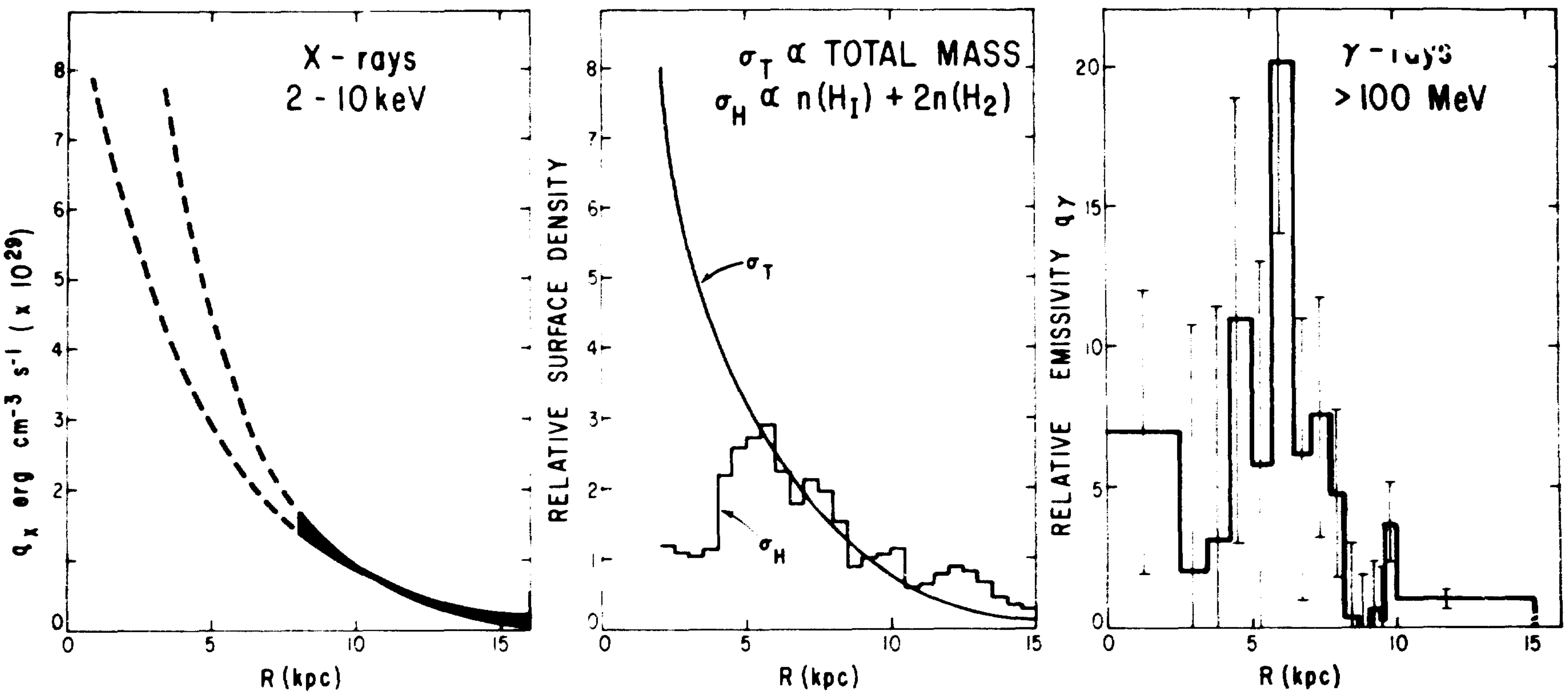
Figure 5 - Expected number of sources of flux $>$ 5 Uhuru counts/s (1 Uhuru ct/s $\approx 2.4\ 10^{-11}$ erg cm^{-2} s^{-1} (2-10 keV)) as a function of mean luminosity for a population of sufficient density to give the derived X-ray ridge emissivity. We assume a luminosity function proportional to L^{-1} and source populations which each cover two orders of magnitude in luminosity.

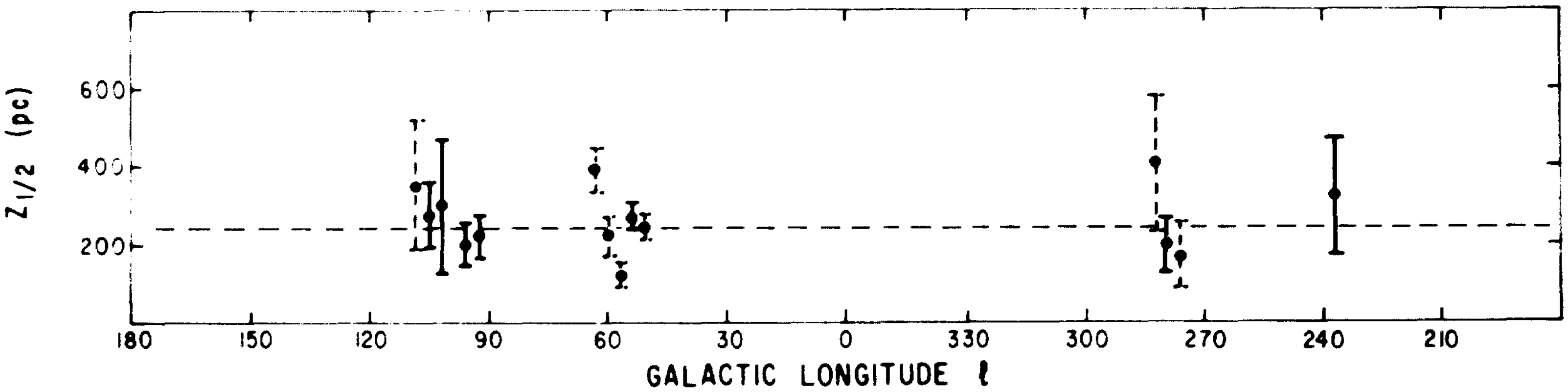
Figure 6 - Logarithmic plots of the predicted number of sources of flux greater than S ct/s, assuming our radially dependent galactic ridge emissivity is entirely due to a population of mean luminosity $10^{32}\ L_{32}$ erg/s and luminosity distribution as given in the text. The upper plot is for Uhuru count rates and is an integral of all sources within 20^{0} of the galactic plane. For comparison, the dashed line is derived from Uhuru observations by Matilsky (1977). The lower plots are for IPC count rates and show the average number per square degree for a galactic center and an anticenter region.

HEAO I-A2 SCANS OVER GALACTIC PLANE

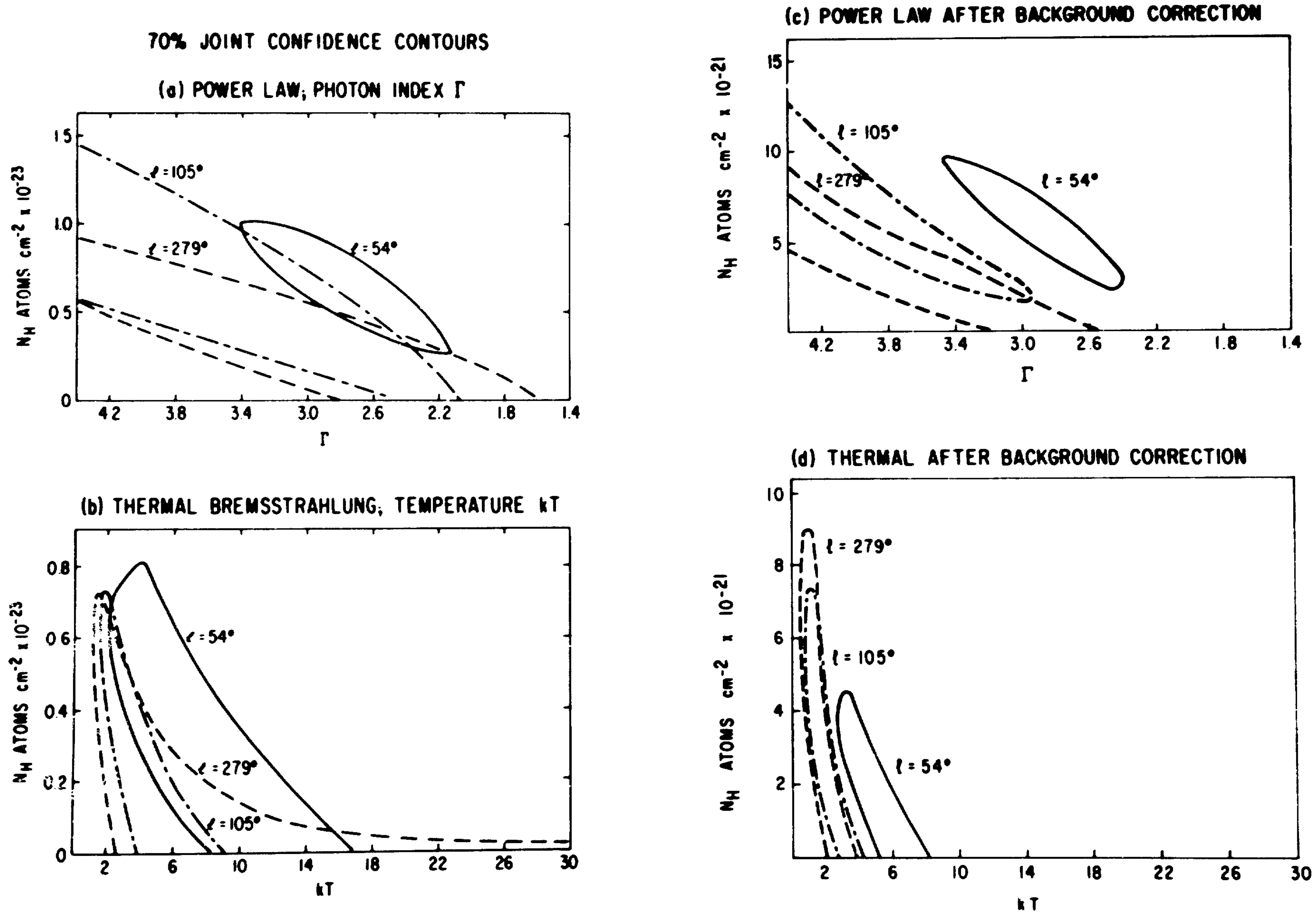


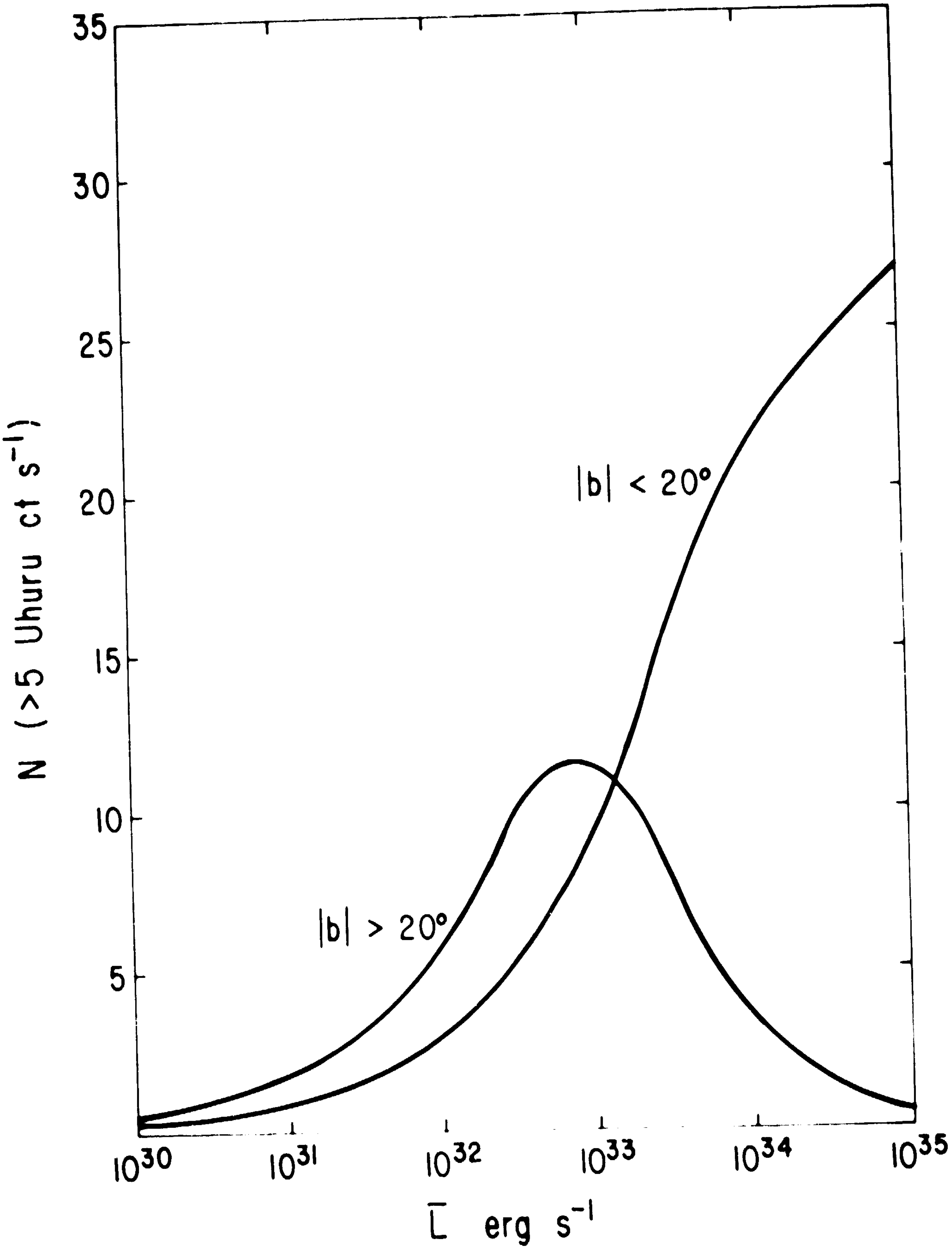

UNIFORM EMISSIVITY MODEL
q erg cm^{-3} s^{-1} (2 - 10 keV) x 10^{30}
12
10
8
6
4
2
0
$Z_{1/2}$ (pc)
600
400
200
180
150
120
90
60
30
0
330
300
270
240
210
GALACTIC LONGITUDE ℓ

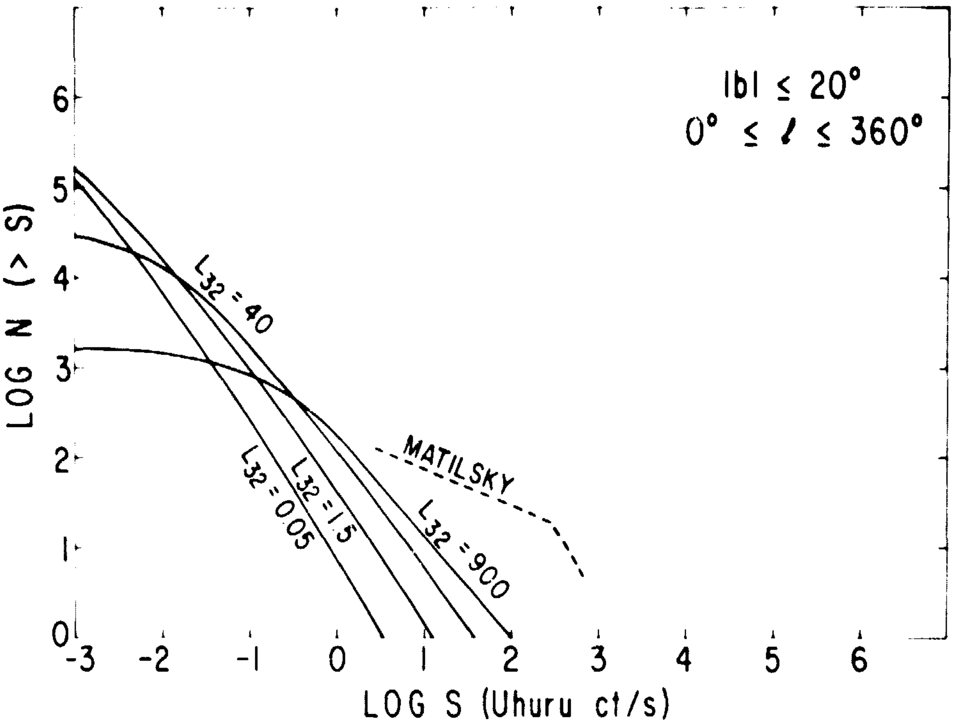

X - rays
2 - 10 keV
q_x erg cm^{-3} s^{-1} (x 10^{29})
0
2
3
4
5
6
7
8
R (kpc)
0
5
10
15
$\sigma_T \propto$ TOTAL MASS
$\sigma_H \propto n(H_I) + 2n(H_2)$
σ_T
σ_H
RELATIVE SURFACE DENSITY
0
1
2
3
4
5
6
7
8
R (kpc)
0
5
10
15
γ - rays
>100 MeV
RELATIVE EMISSIVITY qγ
0
5
10
15
20
R (kpc)
0
5
10
15

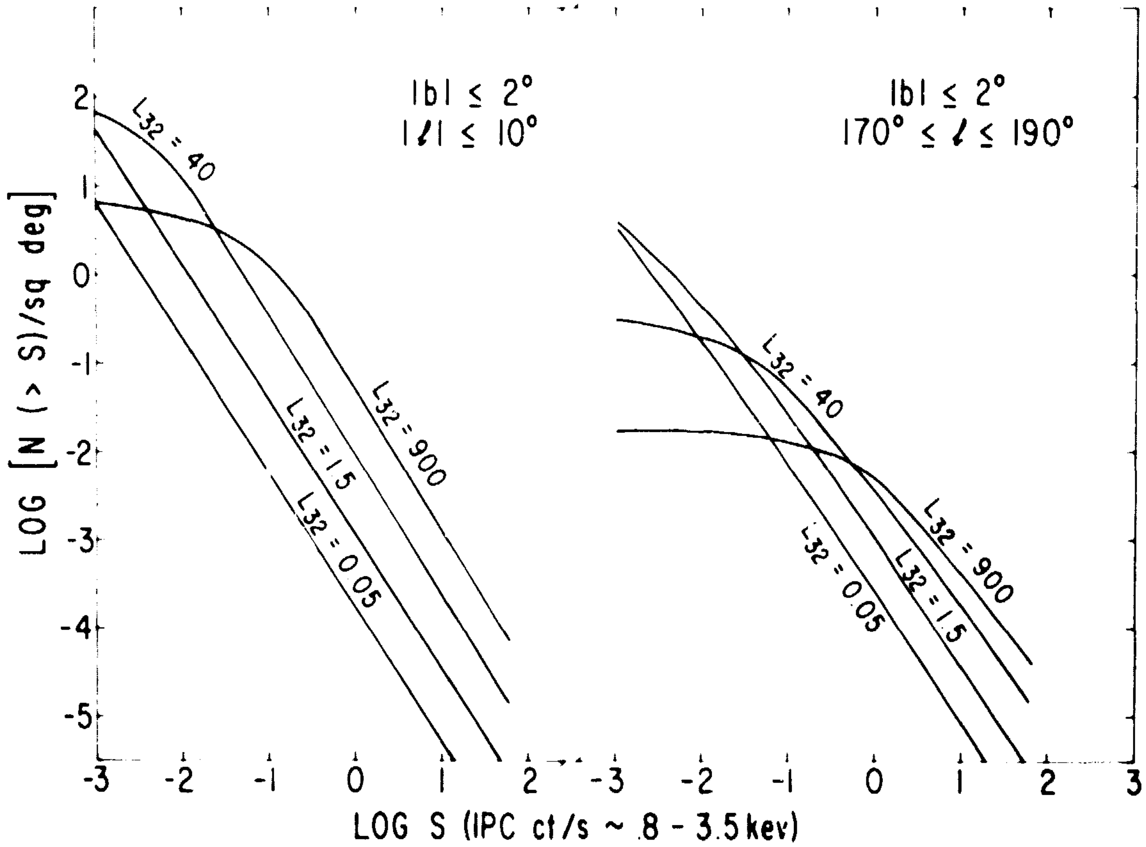

$Z_{1/2}$ (pc)
200
400
600
180
150
120
90
60
30
0
330
300
270
240
210
GALACTIC LONGITUDE ℓ

70% JOINT CONFIDENCE CONTOURS




35
30
25
20
15
10
5
N (>5 Uhuru ct s^{-1})
|b| < 20°
|b| > 20°
10^{30}
10^{31}
10^{32}
10^{33}
10^{34}
10^{35}
$\bar{L}$ erg s^{-1}


|b| ≤ 20°
0° ≤ l ≤ 360°
LOG N (> S)
LOG S (Uhuru ct/s)
L_{32} = 40
L_{32} = 0.05
L_{32} = 1.5
L_{32} = 900
MATILSKY
0
1
2
3
4
5
6
-3
-2
-1
0
1
2
3
4
5
6


|b| ≤ 2°
|l| ≤ 10°
|b| ≤ 2°
170° ≤ l ≤ 190°
LOG [N (> S)/sq deg]
LOG S (IPC ct/s ~ .8 - 3.5 kev)
L_{32} = 40
L_{32} = 900
L_{32} = 1.5
L_{32} = 0.05
L_{32} = 40
L_{32} = 900
L_{32} = 1.5
L_{32} = 0.05
2
1
0
-1
-2
-3
-4
-5
-3
-2
-1
0
1
2
-3
-2
-1
0
1
2
3

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