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STELLAR CONTRIBUTIONS TO THE HARD X-RAY GALACTIC RIDGE

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ABSTRACT

We compare the number density of serendipitous sources in galactic plane *Einstein Observatory* IPC fields with predictions based on the intensity of the *HEAO-1 A2* unresolved hard X-ray galactic ridge emission. We conclude that theoretically predicted X-ray source populations of luminosity $8\ 10^{32}$ to $3\ 10^{34}$ ergs s^{-1} have 2-10 keV local surface densities of less than $\sim 8\ 10^{-4} L_{32}{}^{-1}$ pc^{-2} and are unlikely to be the dominant contributors to the hard X-ray ridge. A new estimate for Be/neutron star binary systems, such as X Persei, which are in this luminosity range and were previously thought to be potentially large X-ray ridge contributors, gives a 2-10 keV local surface density of $\sim 2.6\ 10^{-5} L_{32}{}^{-1}$ pc^{-2}. Stellar systems of low luminosity, $< 4\ 10^{32}$ ergs s^{-1}, are more likely contributors. We find that RS CVn and cataclysmic variable systems contribute 43%±18% of the ridge. This predicts that a more sensitive measurement of the ridge's hard X-ray spectrum should reveal Fe-line emission. We speculate that dM stars are further major contributors.

I. INTRODUCTION.

In a previous paper (Worrall *et al.*, 1982; hereafter WMBS) we describe a measurement with the *HEAO-1 A2* experiment of a galactic component of unresolved X-ray emission. This component, which we refer to as the "ridge emission", was represented by 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) ergs cm^{-2} s^{-1}. The presence of known strong X-ray sources rendered some regions in the galactic plane inappropriate for the WMBS analysis, most notably the entire region within 50^{o} longitude of the galactic center. The exponentially increasing emissivity distribution was therefore only measured for R greater than about 7.8 kpc. The spectrum of the emission was poorly determined, but could fit a power law of photon number index $\Gamma \geqslant 1.5$, ($J(E) \sim E^{-\Gamma}$), or thermal bremsstrahlung emission of temperature kT < 20 keV.

WMBS showed that the allowed luminosity ranges for a source population which can produce the ridge are 40 - 900 L_{32} ergs s^{-1} ("medium" luminosity class) and < 1.5 L_{32} ergs s^{-1} ("low" luminosity class), where L_{32} is the luminosity in units of 10^{32} ergs s^{-1} for 2-10 keV. The former could comprise neutron star or white dwarf binary systems. In particular, Be binary systems, several of which are individually detected, could be significant contributors. The latter could comprise dwarf novae, RS CVn systems and coronally-radiating late-type stars. In this paper we use *Einstein Observatory* Imaging Proportional Counter (IPC) measurements to place firmer limits on the contribution of a medium luminosity population.

II. UNCERTAINTIES INVOLVED IN THE IPC PREDICTIONS

For a population of a given luminosity and of a density required to match the X-ray ridge measurement, we wish to predict the number of sources present at 5σ significance in a given IPC exposure. To make this prediction it is necessary to extrapolate the observed intensity of the ridge from 2-10 keV to the energy band around 1 keV to which the IPC is most sensitive. This extrapolation depends on;

(1). the distribution of absorbing material, since the absorption cross section for X-rays increases with decreasing energy,

(2). the spectral index of the ridge and sources, since the ridge is measured most precisely at ~7 keV and the IPC is sensitive to photons of lower energy.

Concerning (1), we consider it consistent with the other uncertainties to model the neutral atomic hydrogen distribution as a flat disc of uniform density. As in WMBS, the half-thickness is taken as 120 pc, the radius as 16 kpc, and the column density through R(kpc) can be expressed as $N_{HI} \simeq 1.05\ 10^{21}$ R atoms cm^{-2}. Unlike WMBS, we will be considering some directions within 50^{o} longitude of the galactic center where substantial molecular gas is located. Since its amount and distribution are less well known than for atomic hydrogen, we have not modelled it in our calculations. As discussed in section V, for reasonable values it does not affect our conclusions. Concerning (2), since it is our objective to place upper limits on the contribution of a source population to the ridge, we conservatively assume all sources to have the flattest spectral index consistent with results in WMBS and adopt $\Gamma = 1.5$, with no absorption intrinsic to the source.

III. PREDICTIONS.

A source at distance d(kpc) of luminosity L_{32} (2-10 kev) will give an IPC counting rate 1-3.5 keV of $S = 0.015\, L_{32}\, f(N_H,\Gamma) / d^2$, where $f(N_H=3\ 10^{20},\Gamma=1.5)=1$. We find that for $\Gamma = 1.5$, the dependence of N_H (atoms cm^{-2}) on f adequately fits the expression $f(N_H)= 1.06 \exp(-2.75\ 10^{-16} N_H^{\ 0.7})$ for N_H between $3\ 10^{20}$ and 10^{22} atoms cm^{-2}. We choose not to consider photons of energy below 1 keV, since these are stongly affected by galactic absorption, or above 3.5 keV where the telescope efficiency is low.

In figure 1 we give predicted LOG N(>S) - LOG S plots for four representative galactic directions, each of which corresponds reasonably closely to one or more of the IPC fields considered in the next section (noting that our models are symmetric about $|b| = 90^{\circ}$ and $|l| = 0^{\circ}$). Figure 1a shows the distributions assuming the best WMBS fit of an exponential increase of luminosity density with decreasing galactic radius. Since several fields are within a 50° longitude range of the galactic center, we wish to investigate the effect on our conclusions of the rather strong exponential increase. We therefore give in figure 1b the corresponding distributions for a uniform emissivity model. We show results for L_{32} of 40 and 900, values bracketing the medium luminosity source range. We also show $L_{32} = 1.5$, the upper limit of the low luminosity class, and $L_{32} = 0.05$. As in WMBS, a population of mean 2-10 kev luminosity L_{32} is assumed to span two orders of magnitude of luminosity with a density distribution proportional to L^{-1}.

In addition to the galactic sources, we expect a contribution to

LOG N(>S) - LOG S from extragalactic sources. Maccacaro *et al.* (1982) have presented the LOG N(>S) - LOG S distribution for sources in the flux range which roughly corresponds to 1.8 10^{-3} - 1.3 10^{-1} ct s^{-1} (1 - 3.5 keV). Their distribution, written in the notation of this paper, is $N(>S) \cong f(N_H)\ 7\ 10^{-4}\ S^{-1.53}$ /sq. deg. Using our functional approximation for $f(N_H)$, the contribution from this population is given as a dashed line for each plot in figure 1. It is evident that at high latitudes this distribution will dominate a ridge contribution of galactic sources, in agreement with the findings of Maccacaro *et al.*. This also confines the useful directions for our analysis to within roughly 3^o of the galactic plane.

IV. IPC OBSERVATIONS.

We selected those GSFC-requested IPC observations within $2^o.5$ of the galactic plane. We do not expect any selection bias to enter our analysis. In most cases these observations were made primarily to observe a known or suspected X-ray source not from a medium or low luminosity galactic population. In these cases, the target source is first excluded from the considered field of view. We have then searched for serendipitous sources. The background rate varies across each IPC exposure because of vignetting and we construct an average in order to deduce a threshold counting rate for a 5σ detection. Only the region within that obscured by the window support structure is considered. The subsequent field of view is 0.263 sq. deg.

Each entry in table 1 gives the IPC sequence number, central direction in galactic coordinates, the effective exposure in seconds and the threshold counting rate for a 5σ source detection. Only one field, 5175, contained a source. This was just below the detection threshold, but we have made the conservative assumption that it is a valid detection. Figure 1 shows predictions for directions close to the three exposures of longest duration, i.e. those with most weight in this analysis.

V. RESULTS.

Based on the distribution of intensities from Maccacaro *et al.* (1982), the contribution of extragalactic sources to the sum of exposures in table 1 is calculated to be 1.56 sources. The expected number of extragalactic sources from exposure 5175, the only one in which a source was observed, is 0.87. Predictions which include the extragalactic contribution are given in table 2 for the luminosity L_{32} equal to 40 and 900, bracketing the medium luminosity range allowed by WMBS, and $L_{32} = 1.5$, which is the upper bound for the low luminosity population. In figure 2 we plot the expected number of observed sources as a function of their mean luminosity for both the radial and constant models of WMBS. Assuming Poisson statistics, more than one source will be seen 90% (95%, 99%) of the time if the expected number is 3.9 (4.7, 6.6). These expected numbers are indicated by the dashed lines. We conclude that at 95% confidence, mean source luminosities, L_{32}, between ~1 and ~1000 can be rejected as sole ridge contributors for the radial model, and between ~6 and ~400 for the constant model. Thus the medium luminosity population is not allowed if the radial model of WMBS is adopted. For the constant model, the entire luminosity range for the medium luminosity population can only be ruled out with ~90% confidence. Figure 3 shows the 95% confidence maximum percentage contribution to the ridge for each model. Curves of constant local source density are shown for reference.

If actual values for N_H were greatly in excess of those given by our model (section II), the predicted numbers of IPC sources would have been overestimated. We have checked that none of our directions have anomalous values of N_{HI}, by making a comparison with the data of Weaver and Williams (1973), which Burton (1976) summarizes, and for which he indicates appropriate saturation corrections. The N_{HI} values from these data agree to within factors of two with our model estimates, and the total numbers of predicted IPC sources are within 3% agreement with the values given in table 2 and figure 2. The error contributed by our estimated uncertainties in N_{HI} is therefore insignificant to the conclusions of this work. Molecular gas of sufficient quantity to affect our calculations is all confined to longitudes within ~60° of the galactic center, and it has a smaller scale height ($z_{1/2} \simeq 60$ pc) than the atomic gas. The measured quantity is the ^{12}CO distribution of apparent brightness temperature with velocity along the line of sight. There are substantial uncertainties involved in the conversion to molecular gas density and spatial distribution. We have used ^{12}CO temperatures from Burton and Gordon (1978) with the conversion to molecular hydrogen density of Burton and Gordon (1976) to estimate the number of predicted IPC sources when this component of gas is included. The IPC fields 1657, 1749, 4217 and 7462 are the only ones significantly affected. The results are illustrated in figure 2, showing that, although the effect of including molecular gas is not negligible, the final conclusions we have drawn are not affected.

Watson *et al.* (1981) made long duration observations of the galactic center region. We plot the LOG N(>S) - LOG S distribution from IPC observation 950, as given in table 1 of their paper, in the first graph in figure 1. We see that the distribution is comparable to that predicted for medium luminosity sources. However, since our data tend to rule out a large contribution to the ridge from medium luminosity sources, it is more likely that the sources of Watson *et al.* are of a special nature associated with the galactic center itself. The authors already suggest this based on the centrally peaked distribution of their sources within the IPC field of view.

VI. DISCUSSION.

Several authors have pointed to the possible existence of a substantial class of medium luminosity galactic X-ray sources (GXRS). Ögelman and Swank (1974) noted that evolutionary models for the high luminosity GXRS suggest that they could spend extended periods of time as low luminosity sources (L_{32} from 0.001 to 1000) powered by accretion from a stellar wind rather than Roche lobe overflow. The authors estimated a volume emissivity of about 10^{26} ergs s^{-1} pc^{-3}, which is ~42% of the local ridge emissivity, but they point out that several rather uncertain assumptions were necessary for the calculation. Such a luminosity is also possible for accreting white dwarfs (Kylafis and Lamb, 1979), but the density of such sources is not known.

The observed source counts in the 3U and 4U catalogs (Giacconi *et al.*, 1974; Forman *et al.*, 1978) have been given as evidence for medium luminosity sources. Matilsky (1977) argued that the different dispersion in galactic latitude for bright and faint GXRS indicates the existence of a class of sources with $L_x \simeq 10^{34}$ ergs s^{-1}. More detailed analysis by Protheroe and Wolfendale (1980) of the distribution in longitude suggests the existence of sources with luminosities less than 10^{36} ergs s^{-1}.

Two binary systems with $L_x \simeq 10^{33}$ ergs s^{-1} are known: X Per and γ Cas. Mushotzky *et al.* (1977) suggested that Be star binary systems such as these could be responsible for the hard X-ray ridge. Rappaport and van den Heuvel (1982) have speculated that Be star transient X-ray binary systems have a quiescent state in which a solar wind from the Be star feeds a neutron star, as is thought to be the case for X Per and γ Cas. They estimate that ~50 such Be/neutron star systems could be within 2.5 kpc (consistent with the fact that two such systems, X Per and γ Cas, are known within 350 pc), which at a luminosity of 10^{33} ergs s^{-1} is ~2.6 $10^{-5} L_{32}{}^{-1}$ pc^{-2} and provides only 2.4% of the surface emissivity of the ridge. The scale height of these systems also indicates that they do not make a significant contribution to the ridge. While the measured half-thickness of the ridge is 241 pc, the scale height of B stars is only 60 pc (Allen 1973) and the average distance from the plane for the 4 Be X-ray transients with known distances, together with X Per and γ Cas, is 50 ± 14 pc. Runaway velocities from supernovae have been suggested by Rothenflug, Rocchia and Cassé (1979) as a mechanism to broaden the scale height of such systems, but this effect does not appear to be important for Be systems which are bright X-ray sources.

Although there are reasons to believe that a substantial number of medium luminosity GXRSs may exist, we have shown that they are not a dominant constituent of the galactic ridge (see figures 2 and 3). Their local surface density is less than ~8 10^{-4} ${L_{32}}^{-1}$ pc^{-2}. For reasons discussed in WMBS, diffuse emission mechanisms probably do not make a significant contribution to the galactic ridge. Rather, we now turn our attention to low luminosity binary sources, specifically RS CVn and cataclysmic variable (CV) stars.

The X-ray characteristics of CVs have recently been reviewed by Cordova and Mason (1982). Swank *et al.* (1981) summarize observations of the X-ray spectra of RS CVn stars. Although a wide variety of binary systems are included in these two classes, there appear to be some common characteristics which are relevant to a computation of their volume emissivity:

1). The sources have two-temperature spectra, one being less than 1 keV, the other greater than 5 keV.

2). Their luminosities in the 2-10 keV band range up to about 10^{32} ergs s^{-1}.

3). Their intensities are variable by factors of at least two.

We now use the high latitude complete survey of Piccinotti *et al.* (1982) to estimate the volume emissivity of such sources using the standard Schmidt estimator (Schmidt 1968). Because of the different energy response of the IPC and the lack of complete surveys, we cannot use the

IPC results despite the larger number of detected sources. Table 3 presents the data for the RS CVn and CV sources detected in the first pass over the sky from Piccinotti *et al.*. The contribution of the ith source to the local volume emissivity is given by

$$q_i = \frac{L_i \, 4\pi}{V_{mi} \, \Omega}$$

in which L_i is the luminosity of the detected source, Ω is the solid angle of the survey (8.17 sr) and V_{mi} is the volume in which a source of the same luminosity would have a flux above the limiting sensitivity of the survey. Since the distances to the sources is less than the scale height of the disk and absorption is negligible at high latitudes, we have assumed spherical symmetry in calculating V_{mi}. The resulting volume emissivity is 1.0 10^{26} ergs s^{-1} pc^{-3}. Since 92% of the sources in the catalogue have been identified, we have assumed that the identified sources contribute 92% of the true volume emissivity. This may underestimate the true volume emissivity since RS CVn binaries and CVs are more difficult to identify than Seyfert 1 galaxies or clusters of galaxies. The variance on the estimator depends on the luminosity function (Felten 1976). The functional form 1.7 $10^{25}L^{-2}$ $ergs^{-1}$ s pc^{-3} for L between 2 10^{30} and 4.4 10^{32} ergs s^{-1} approximates the data and implies that $\sigma \simeq 0.4\ 10^{26}$ ergs s^{-1} pc^{-3}. We have neglected errors due to the uncertainties in distances to the sources. Thus we estimate that RS CVn binaries and CVs contribute 43% ± 18% of the ridge.

For sources with luminosities $\leq 10^{30}$ ergs s^{-1}, the more sensitive surveys of the *Einstein Observatory* must be used despite its different energy band. Rosner *et al.* (1981) find that the local volume emissivity in the 0.1 to 3.5 keV energy band for dwarf stars is dominated by dM stars, which contribute 1.5 10^{27} ergs s^{-1} pc^{-3}. Emission from dwarf stars is thought to be due to optically thin thermal bremsstrahlung from coronal plasma, and preliminary analysis of IPC spectra indicates characteristic temperatures of $\leqslant$ 1 keV (Vaiana *et al.* 1981). However the relatively poor spectral resolution of the IPC would make the detection of a weak high temperature component difficult. Detection of two-temperature coronal emission from the RS CVn systems (Swank *et al.* 1981), the G5 III star Capella (Holt *et al.* 1979) and Algol (White *et al.* 1980), with the Solid State Spectrometer of the *Einstein Observatory* (SSS), makes the existence of a high temperature component from dM stars plausible. X-ray spectra with the good resolution of the SSS exist for only two dM stars: Wolf 630AB and AD Leo (Swank and Johnson 1982). Each star has both a high- and low-temperature component. The luminosity of the hot component is about one third that of the cooler component. It should however be noted that these are two of the most X-ray luminous dM stars known. Thus, their spectra may not be typical. The volume emissivity in the 2-10 keV band need only be 7% of that calculated by Rosner *et al.* (1981) for the 0.1 to 3.5 keV band for dM stars to contribute 50% of the hard X-ray galactic ridge emission. The scale height of 350 pc for dM stars (Allen 1973) is comparable to that of the ridge, indicating that they could make a substantial contribution. More observations, with resolution comparable to the SSS, of weak sources are needed to determine the fraction of the X-ray luminosity of dM stars which is in the hard X-ray band, and its possible dependence on soft X-ray luminosity.

VII. CONCLUSION

The number of serendipitous sources seen during observations of the galactic plane with the IPC shows that it is unlikely that X-ray sources with 2-10 keV luminosities from ~8 10^{32} to ~3 10^{34} ergs s^{-1} are dominant contributors to the hard X-ray galactic ridge. Their surface density is less than ~8 $10^{-4} L_{32}^{-1} pc^{-2}$. In particular, Be/neutron star systems such as X Per are not expected to be dominant contributors, both because the 2-10 keV luminosity is roughly 10^{33} ergs s^{-1} and their scale height is too small. However, these systems could be a large class of X-ray emitters of density $\leq$4 10^{-8} pc^{-3}. The unresolved nature of the ridge had previously been used (WMBS) to rule out sources with luminosities greater than ~9 10^{34} ergs s^{-1}.

Lower luminosity stellar systems are likely to be major contributors to the ridge. We have calculated that RS CVn and CV systems with 2-10 keV luminosities between 2 10^{30} and 4 10^{32} ergs s^{-1} contribute about 43% ± 18%. The measured spectra of the brighter members of these classes indicate that, with more sensitive instruments, Fe-line emission would be observed in the ridge spectrum.

Stars with even lower X-ray luminosities are possible major contributors to the ridge, but here the case is more speculative. The volume emissivity of dM stars in the 0.1 to 3.5 keV energy band is many times that deduced for the ridge in the 2 to 10 keV energy band, and they have approximately the right scale height. Observations of two bright dM stars show that they both have a significant fraction of their X-ray emission above 2 keV, making it plausible that such stars are important contributors. Observations by future hard X-ray experiments are needed for a more quantitative estimate.

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Table 1

Einstein IPC Fields

Sequence Number	l	b	Effective Exposure (secs)	5σ Sensitivity Limit (10^{-3} cts s^{-1})
1657	21.5	-0.89	5645	10.0
1749	33.2	0.7	2129	20.0
1751	63.4	1.0	2808	16.8
1752	252.9	-0.8	2678	15.1
1764	69.8	-2.2	8228	7.6
1765	60.0	0.0	8445	8.7
4217	24.3	-0.1	4160	12.3
4558	102.1	-0.8	1988	20.0
5175	57.0	0.0	43140	2.3[a]
7237	201.4	0.7	12979	5.2
7256	302.3	-0.1	1579	26.2
7398	347.8	2.2	13066	5.7
7462	29.7	-0.3	3637	20.8

a - Source of 2.2 10^{-3} cts s^{-1} (4.9σ). No other exposure contains a candidate source.

Table 2

Probability of Populations of Luminosity L_{32} contributing the X-ray Ridge Based on the 13 IPC Fields of Table 1.

L_{32}	Total sources	Radial Emissivity: Predicted	Radial Emissivity: % Prob. of Agreement	Constant Emissivity: Predicted	Constant Emissivity: % Prob. of Agreement
900	1	5.48	2.7	3.79	10.8
40	1	11.23	0.016	6.28	1.3
1.5	1	5.3	3.1	3.72	11.4

Table 3

Low Luminosity X-ray Binaries

Name	Type	d (pc)	Flux[a] (R15)	L_x (10^{30} ergs s^{-1})	Ωq_i (10^{24} ergs s^{-1} pc^{-3})
HR1099	RS CVn	33[b]	1.27	3.5	22.5
1052+60	RS CVn	160[c]	1.34	86.2	4.5
AM Her	CV	75[d]	4.11	58 1	5.5
0311-22	CV	75[e]	2.64	37.3	6.9
0526-32	CV	75[e]	1.99	28.1	7.9
EX Hyd	CV	150[d]	4.41	249.0	2.6
U Gem	CV	75[d]	1.36	19.2	9.6
2252-035	CV	220[f]	2.36	287.0	2.5
TOTAL					62.0

a - Piccinotti *et al.* (1982)
b - Bopp and Fekel (1976)
c - Schwartz *et al.* (1979)
d - Cordova and Mason (1982)
e - Assumed
f - Patterson and Jablonski (1981)

Figure Captions

Figure 1.

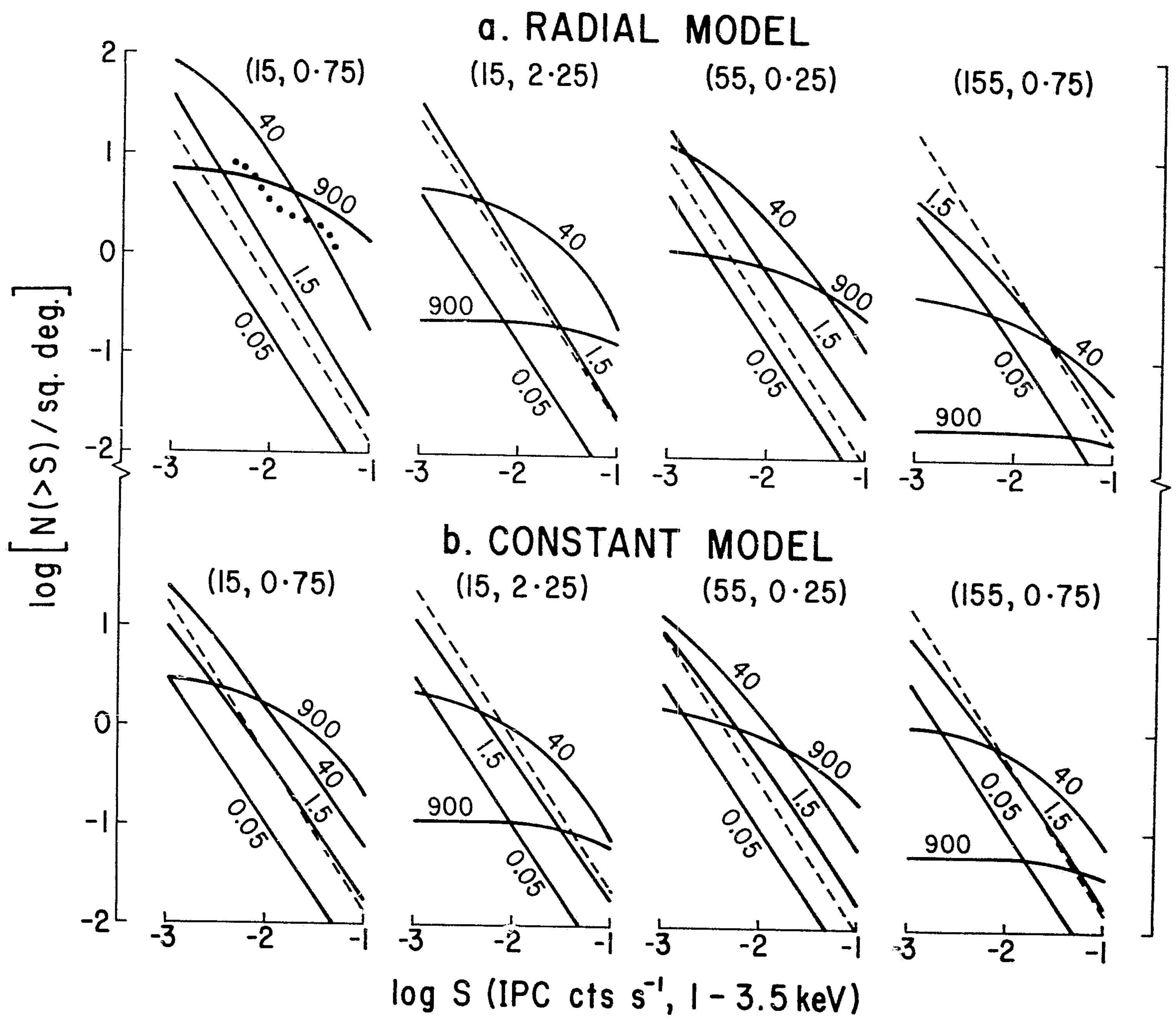
Representative plots of LOG N(>S) (/sq.deg.) - LOG S (ct s^{-1}, 1-3.5 keV) for various directions (l,b). The numbers on the curves represent the mean 2-10 keV luminosity of the population in units of 10^{32} ergs s^{-1}. Predicted extragalactic contributions, from the results of Maccacaro *et al* (1982), are indicated as dashed lines. la assumes the radially dependent emissivity model of WMBS and lb assumes the local emissivity everywhere in the disc. The dotted line on the first graph represents observations of Watson *et al.* (1981) (see section 5).

Figure 2

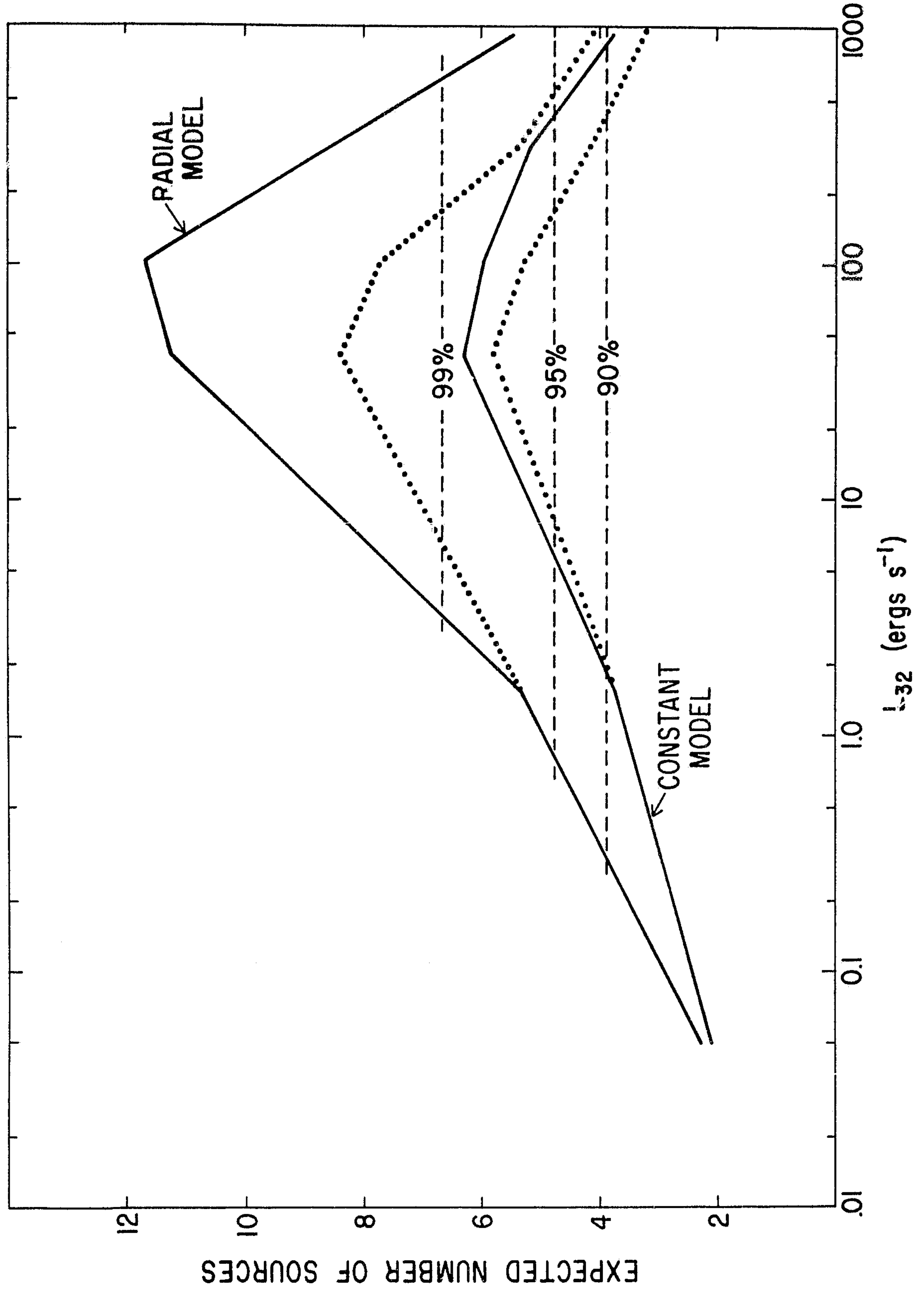
Sum of the expected number of sources in the 13 exposures as a function of the luminosity in units of 10^{32} ergs s^{-1}. An extragalactic contribution of 1.56 sources is included. The dotted lines are estimated when molecular gas is included. A population with luminosity for which the curve lies above a dashed-line confidence contour can be excluded as a 100% contributor to the ridge with the given percentage confidence.

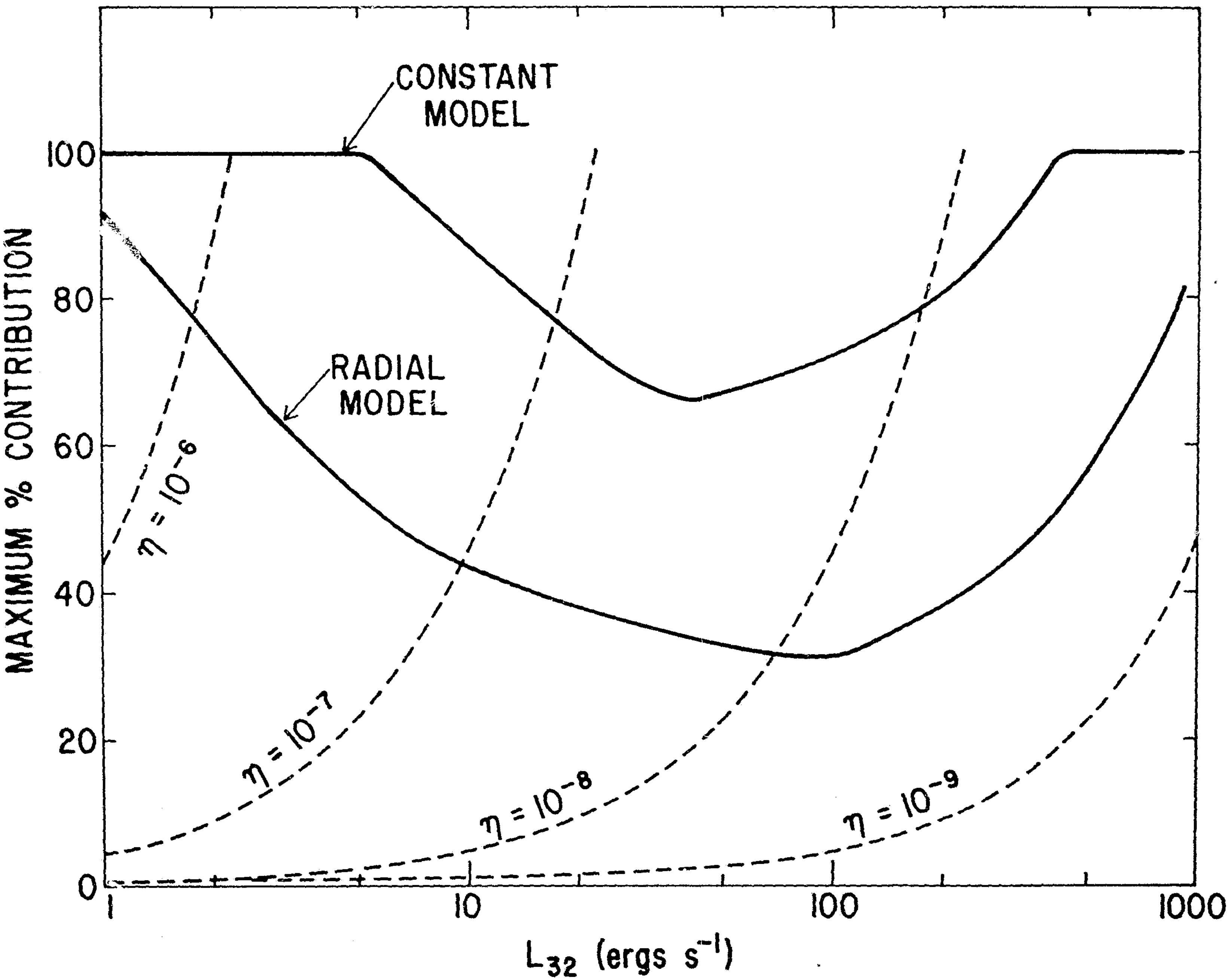
Figure 3

The 95%-confidence upper limits to the unresolved emission for source populations of given luminosities in units of 10^{32} ergs s^{-1}. Curves of constant local source density, η, in units of pc^{-3}, are shown for reference.



a. RADIAL MODEL
(15, 0·75)
(15, 2·25)
(55, 0·25)
(155, 0·75)
b. CONSTANT MODEL
(15, 0·75)
(15, 2·25)
(55, 0·25)
(155, 0·75)
40
900
1.5
0.05
log [N(>S)/sq. deg.]
log S (IPC cts s⁻¹, 1 – 3.5 keV)


EXPECTED NUMBER OF SOURCES
L_{32} (ergs s^{-1})
RADIAL MODEL
CONSTANT MODEL
99%
95%
90%
2
4
6
8
10
12
.01
0.1
1.0
10
100
1000



CONSTANT
MODEL
RADIAL
MODEL
$\eta = 10^{-6}$
$\eta = 10^{-7}$
$\eta = 10^{-8}$
$\eta = 10^{-9}$
100
80
60
40
20
0
1
10
100
1000
MAXIMUM % CONTRIBUTION
L_{32} (ergs s^{-1})