OBSERVATIONAL RESULTS ON DIFFUSE COSMIC X-RAYS

(Invited Discourse)

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Abstract. The present status of observations of the diffuse cosmic X-rays is discussed. The energy spectrum in the energy range 1–100 keV has been well established. The flux around 0.25 keV appears to be rather high. The basis of the classical argument that the integration of normal galaxies in the universe is not sufficient to explain the diffuse X-ray flux is re-examined. Recent observations around 0.25 keV are discussed and results are compiled.

1. Introduction

The purpose of this article is to discuss the present status of the observational investigations of the diffuse cosmic X-rays. The diffuse component of cosmic X-rays has been detected since the discovery of the cosmic X-rays. Experimental results have not been as convincing as those for point sources due to experimental difficulties in distinguishing the true cosmic component from the spurious component of terrestrial or local origin. Recently however more careful non-X-ray background discriminations have become common by means of the earth-shadowing effect, the shutter and the techniques of the rise time discrimination of counter pulses [1].

First, the energy spectrum will be discussed. The spectrum in 1–100 keV range has been established. The fact that the flux at 0.25 keV is consistent with the extension of a power law spectrum from 1–100 keV range or even higher is very important. Secondly, the argument to explain the diffuse component in terms of the integration of extragalactic sources will be discussed. Several observations in 0.25 keV band will be discussed. From the observations, in spite of some disagreement among them, interstellar absorption of very soft X-rays is concluded. Some details of the interstellar absorption are also discussed.

2. Energy Spectrum

The spectrum in the energy range of 1–100 keV has been well established. Figure 1 shows the results of various observations [2] which may be well represented by a power law $E^{-1.7\pm0.2}$ in the energy range 1–100 keV. It appears that the spectrum tends to steepen for higher energy and the exponent, 2.0, shows a better fit for 100–1000 keV. Indication of a *break* or *knee* of the spectrum, though not yet conclusive, is interesting from the point of theoretical interpretation of the diffuse cosmic X-rays. The energy range 100–1000 keV and beyond 1000 keV will have to be explored more thoroughly.

Several measurements have been carried out recently at energies close to 0.25 keV [3, 4, 5, 6, 7, 8]. A compiled value of the flux outside of the galaxy is represented by a double circle in the figure. The flux at 0.25 keV is on or above the extrapolation of the

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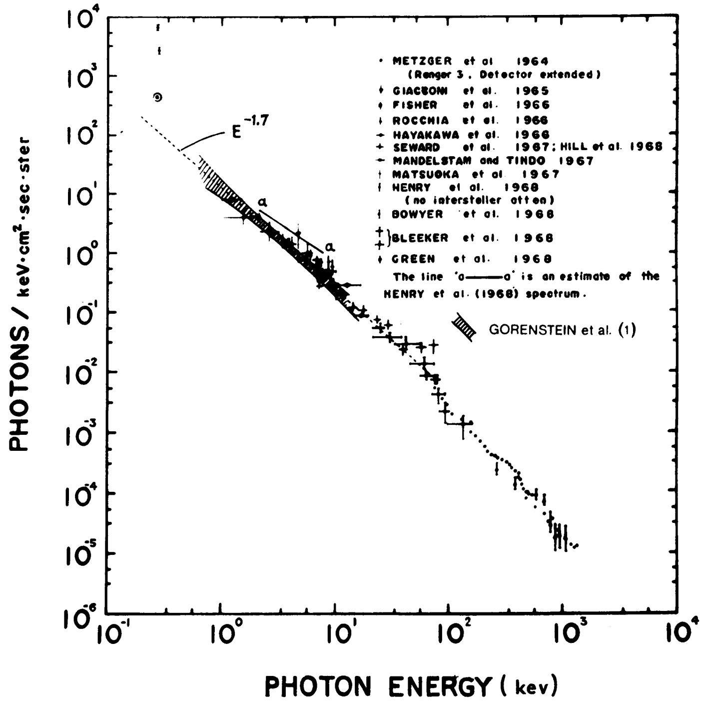

Fig. 1. Energy spectrum of the diffuse cosmic X-rays. The data are represented by a power law spectrum $E^{-1.7\pm0.2}$, in the energy range 1–100 keV. Measurements at 0.25 keV are compiled and the flux corrected for interstellar absorption is represented by a double circle.

spectrum at high energy range. The apparent absence of the absorption of the diffuse X-rays outside the Galaxy suggests that they originate in the intergalactic space and not in the galaxies in the universe. [9].

3. Extragalactic Objects

There has been a classical argument [10] that the contribution by galaxies in the universe is insufficient by a factor of 10–100 to explain the observed flux of the diffuse X-ray background. The argument was simply as follows: If we take the intensity of Tau-X-1 (Crab Nebula) as a standard we have approximately 20 sources of the intensity $\frac{1}{4}$ Tau-X-1. The distance to sources are 1.5 kpc for Tau-X-1 and 10 kpc or 3 kpc for other sources depending upon whether we consider other sources to be as far as the galactic center or to be in the nearby galactic arm.

If we take the absolute X-ray luminosity of Tau-X-1 to be 1, the luminosity of other sources for each assigned distance respectively is 10 and one approximately. The total number of sources, may be 100 or 1000 for these respective cases. Thus, the luminosity (X-ray) of our own galaxy may be equivalent to 1000 Tau-X-1. Assuming that all galaxies in the universe are similar to our galaxy, we may estimate the contribution of galaxies up to the Hubble distance. The fact that this estimate is less than the observed flux by a factor of 10–100 has led to a variety of theoretical considerations on the diffuse cosmic X-rays.

It is still worthwhile to re-examine the above classical arguments and ask the following questions.

(1) Is not the X-ray luminosity of our galaxy brighter than estimated on the basis of observed galactic point sources by a factor of ten or more?

The question (1), in other words, is whether there is a possibility that numerous unresolved and yet unobserved galactic sources increase the X-ray luminosity of our galaxy by some factor.

The observation of M31 (Andromeda Nebula) has been suggested in this respect. The Andromeda Nebula is known to be similar to our galaxy and its observation will provide an almost straightforward measurement of the absolute X-ray brightness of the galaxy. Its expected intensity is approximately $\frac{1}{300}$ of Tau-X-1 or more and is now within the possibility of observation but it has not been measured.

(2) Do some extragalactic objects much brighter than our galaxy contribute to the diffuse component more than normal galaxies? For example, cannot one percent of galaxies be brighter than a normal (our) galaxy by a factor of 1000 and altogether could the universe be ten times brighter?

Regarding question (2), if the diffuse component is mainly contributed by very bright objects, the intensity distribution of X-rays in the celestial sphere may not be as smooth as is expected due to the finite number of objects included in the field of view of the detector. We may derive a relation of the size of the field of view and the expected roughness (or granulation) of the diffuse component for an assumed brightness of each bright object.*

For example, if the density of the objects is one thousandth and their brightness is ten thousand times that of normal galaxies, with the field of view $4° \times 4°$ we may detect a fluctuation of the diffuse component of the order of 10%. Up to the present no evidence for the granulation has been reported.

Notice that in the Virgo cluster at a distance of 10000 kpc three thousand galaxies crowd together and they may represent all kinds of galaxies (except for cosmological effect). If they are all like our galaxy, the total brightness of the cluster may be of the order of $\frac{1}{10}$ of Tau-X-1. If the *average* brightness is ten times the estimate of our galaxy, we may expect its brightness to be similar to Tau-X-1. Since the cluster spreads in a broad area in the sky it is not obvious that it should have been detected. One may design an experiment to detect the cluster and study if extraordinarily bright objects exist in it.

4. Interstellar Absorption of Soft X-Rays

The apparent isotropy of the diffuse component suggests the extragalactic origin. Most convincing evidence for the extragalactic origin may be acquired by observing the galactic or interstellar absorption of the diffuse component.

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* The details of the argument will be published separately.

Figure 2 shows the expected interstellar transmission for various energies based upon Bell and Kingston's calculation [11]. The abscissae cover the range of the amount of hydrogen atoms along the line of sight corresponding to various galactic latitudes. It is seen that in the energy range >1 keV the galaxy is essentially transparent, for 0.5 keV a galactic latitude effect at low latitude is expected and for <0.25 keV, due to a strong interstellar absorption, a galactic latitude effect is expected only at high galactic latitudes.

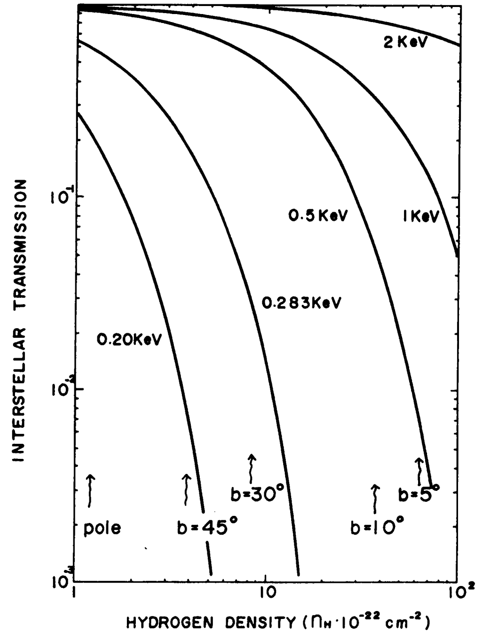

Fig. 2. Interstellar transmission of soft X-rays computed based upon Bell and Kingston's calculation. n_H is the amount of hydrogen atoms along the line of sight. Corresponding galactic latitudes (b^{II}) are indicated.

5. Observation of 0.25 keV X-Rays

Techniques of detecting <0.5 keV X-rays quantitatively and with a reliability are not easy. Several groups have managed to fabricate proportional counters with extremely thin plastic windows so that the transmission band near the carbon K-absorption edge (0.28 keV) may be used. Spectral responses for few typical proportional counters of this type are shown in Figure 3.

Table I tabulates the features of the rocket experiments performed so far. Figure 4 summarizes rough sketches of observed regions of the sky in these experiments reproduced from the papers of these authors.

In what follows we shall summarize the experimental results and examine whether all the results may be combined. In the Berkeley experiment [3] if some observed patchiness in the sky is ascribed to local sources and can be ignored, there remains a

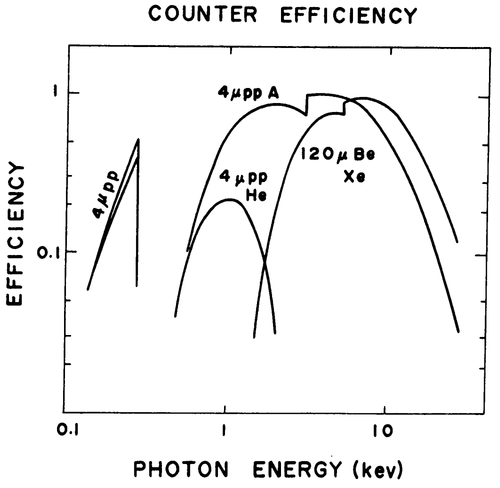

Fig. 3. Spectral response of proportional counter with thin plastic window, polypropylene (pp), and Be window. Transmission band at carbon *K*-absorption edge (0.28 keV) is clear.

TABLE I
Observations of soft X-rays (> 44 Å)

	Counter window	Gas	η(0.28 keV)	Calibration	A, Ω	Flight
Berkeley	$\frac{1}{8}$ mil mylar 200 Å nichrome	A	0.16	parallel counter Fe^{55} ground	500 cm^2 0.021 str	Dec. 13, 66 0630 UT Brazil
N.R.L.	0.15 mil mylar 0.5 mil mylar	A A	0.12		200 cm^2 200 cm^2 0.024 str	Sep. 7, 67 2021 MST
L.R.L.	60 $\mu g/cm^2$ formvar	Ne-meth A-meth	0.65	nose cone isotope		May 14, 68 2038 Hawaii
Wisconsin	290 $\mu g/cm^2$ kimfol 585 $\mu g/cm^2$ mylar		0.42 0.14		250 cm^2 250 cm^2 0.019 str	Sep. 21, 68 0345 GMT
Calgary	0.25 mil mylar + 1350 Å Al		0.02	ground	30 cm^2 0.117 str	Oct. 8, 68 0505 UT Canada
Nagoya- Tokyo	4 μ polypropylene 5 mil Be	He A Xe	0.45 –	CK Fe^{55} shutter	200 cm^2 190 cm^2 0.015 str	Jan. 14, 69 1900 JST K.S.C.

general tendency showing the galactic latitude effect or interstellar absorption in the range of $n_H \approx 2\text{–}15 \times 10^{20}/cm^2$. The attenuation appeared less than the estimate based upon Bell and Kingston's calculation.

In the NRL-experiment [4] the flight of the rocket was controlled to cover several

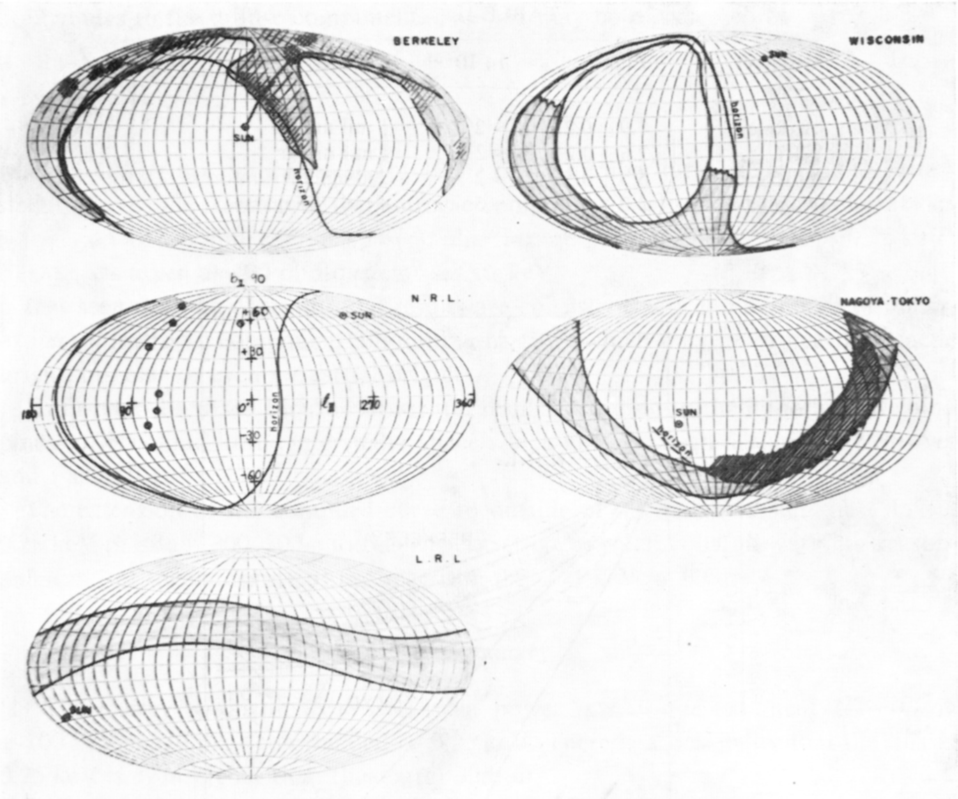

Fig. 4. Region of the sky (galactic coordinate) scanned with 0.25 keV counters by various investigators (shadowed area).

spots in the sky including the low galactic latitude region and a region where the n_H is smallest (near the pole). Some points at low galactic latitude which showed strong intensities were attributed to cool (compared to normal X-ray sources) and nearby X-ray sources. This may imply the existence of numerous sources of this kind.

The region of the sky scanned by LRL group [5] covered the range of $n_H > 4 \times 10^{20}/\text{cm}^2$. Except for some irregularity the intensity distribution was flat and no apparent galactic latitude effect was observed.

In the Nagoya-Tokyo experiment [6] the field of view of one of the detectors was designed in such a way that its long axis is precisely parallel to the galactic equator and hence the correspondence between the rocket azimuth and the galactic latitude is simple. In the observed range of $n_H > 4 \times 10^{20}/\text{cm}^2$ no obvious attenuation was detected. Yet an apparent difference was observed in counting rates when the shutter in front of the detector was open and closed.

Kraushaar and the Wisconsin group [7] covered a region extending from low galactic latitudes to high galactic latitude and observed a clear galactic latitude

TABLE II

Observer	Flux	n_H 10^{-20}	Counter window
Berkeley	1.9 ± 0.2	~ 2	$\frac{1}{8}$ mil mylar
NRL	2.6 ± 0.2	~ 2	$\frac{1}{8}$ mil mular
Wisconsin	5.5 ± 0.5	~ 2	290 μg/cm^2 kimfor
Nagoya-Tokyo	2.0 ± 0.2	~ 5	4 polypropylene

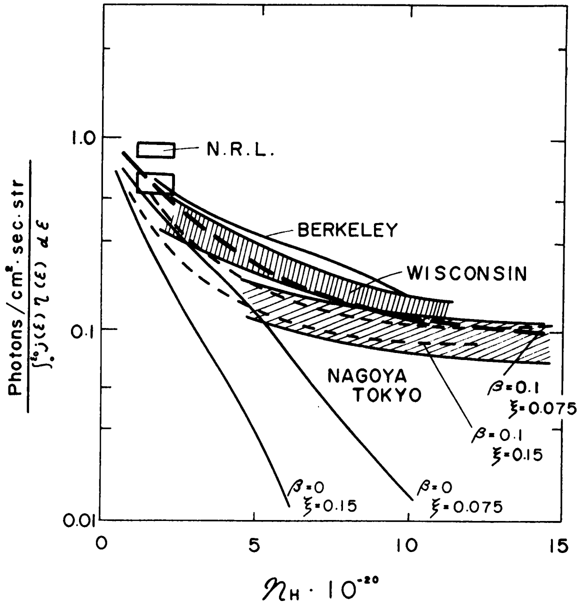

Fig. 5. Observed fluxes in 0.25 keV band of X-rays. The results are consistent with each other within a factor of 1.5–2 indicating the interstellar attenuation.

effect. The effect was also observed at a higher energy range 0.48–0.96 keV.

We summarize the *observed* fluxes in 0.25 keV band in Table II.

Results are summarized in Figure 5. If we ignore discrepancies by a factor of 1.5 or 2 considering experimental difficulties and some ambiguities in the estimate of the background counts to be subtracted to obtain the flux for low galactic latitudes, the combined results may be represented by the dashed curve.

If we accept this compilation, we find that the resulting attenuation curve is not compatible with the absorption by homogeneous interstellar gas of any composition which is represented by curves indicated as $\beta = 0$ in Figure 5. We have to explain the apparent flattening of the attenuation curve for higher values of n_H.

Curves in Figure 5 represent examples of calculated attenuation curves on an assumption that in addition to the component of extragalactic origin an isotropic flux contributes to the diffuse component. The flux may be represented as

$$\int_0^{\varepsilon_0} \frac{e^{-\tau}+\beta}{1+\beta} j(\varepsilon)\,\eta(\varepsilon)\,\mathrm{d}\varepsilon,$$

where $\tau = n_H \cdot (\varepsilon/\varepsilon_0)^{-3.2}(0.84+21.4\xi)\cdot 10^{-2}$; ξ: the number ratio of He/H in the interstellar gas; β: the fraction of the isotropic component; $j(\varepsilon)$: the counter efficiency as a function of photon energy ε; $\eta(\varepsilon)$: the flux at photon energy ε; $\varepsilon_0 = 0.28$ keV; η $(\varepsilon = \varepsilon_0)$ is taken as 400 photons/cm^2 sec str keV.

It is seen that the observational results are consistent with the existence of an *unexplained* isotropic component amounting to 10%, which may be of nearby galactic origin, or solar or even terrestrial origin.

Kraushaar discussed their experimental result according to the hypothetical clumpiness of H I cloud in the interstellar space which has also been discussed by Bowyer and Field [12].

The extension of the compiled curve to outside of our galaxy results in a flux at 0.28 keV of about 300–500 photons/cm^2 sec str keV which is barely within a reasonable limit of the extension of the spectrum for $>$ 1 keV in Figure 1.*

6. Summary

(1) The energy spectrum expressed by a power law of the exponent 1.7 ± 0.2 in 1–100 keV range may be extended to 0.25 keV. There is a possibility that the flux at 0.25 keV is even higher than this extrapolation.

(2) A break of the spectrum near 100 keV is suspected though its existence is not conclusive yet.

(3) Several experiments have been suggested in relation to the model of superposed extragalactic sources for the explanation of the diffuse X-rays.

(4) Measurements of the very soft X-ray (0.25 keV) flux by several groups are compiled. Evidence for the interstellar attenuation indicating the extragalactic origin was obtained. The results, however, are in some disagreement with a theoretical prediction and this disagreement has been discussed.

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* An experiment by Wilson *et al.* of Calgary [8] is in disagreement with other experiments. They obtained a high flux at 0.25 keV, about 3000 photons/cm^2 sec str keV. The difference between this experiment and other experiments is that the counter window of Calgary experiment is relatively thick and the transmission at 0.25 keV is only a few percent whereas for other experiments the transmission was in the range of 15–40%. It may be dangerous to correct the data for such small transmission, but, on the other hand, the technical difficulties increase for a thinner window. This disagreement has not been thus far understood.

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