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# LOW-ENERGY DIFFUSE X-RAYS

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## ABSTRACT

Measurements of diffuse cosmic X-rays in the energy region $E < 284$ eV and 0.5–1 keV show that there is a clear excess over the extrapolated higher-energy power law and that the spatial distribution is not consistent with a purely extragalactic origin. The excess intensity cannot have its origin in interstellar processes unless ionization rates larger than $10^{-13}$ (s H)$^{-1}$ can be accommodated.

## I. INTRODUCTION

Quantitative agreement among the several reported measurements of diffuse X-rays below 1 keV (Bowyer *et al.* 1968; Henry *et al.* 1968; Baxter, Wilson, and Green 1969*a*, *b;* Bunner *et al.* 1969; Hayakawa *et al.* 1970*a;* Henry *et al.* 1971; Shukla and Wilson 1971) is not good, but most of the data imply that the intensity just below the carbon *K*-edge is well above that to be expected from a simple extrapolation of the power law that fits the higher-energy data. There is good evidence that while the intensity near 250 eV decreases with decreasing galactic latitude, the magnitude of the decrease is not consistent with a totally extragalactic origin and absorption by the amount of gas measured by the 21-cm emission surveys. The high intensity has been interpreted both as evidence for a high-density hot intergalactic gas and as the unresolved contributions of discrete galactic sources. Unresolved galactic sources, cloud structure of the interstellar gas, and a smaller-than-normal helium abundance have all been suggested as explanations of the small apparent absorption. A review article covering these matters has been prepared by Silk (1970).

There are several sources of possible observational confusion, particularly in the region near 250 eV. Among these are the presence of low-energy charged particles, unsuspected ultraviolet sensitivity of the detectors, scattered solar X-rays, and X-ray collimator reflections which result in energy-dependent solid angles. We report here the results of a rocket-borne observation which we believe provides significant clarification of these matters.

## II. THE DATA

The Aerobee rocket was launched 1969 December 5 at 06:38 GMT from White Sands, New Mexico. The detectors were two proportional counters with an effective area of 470 cm$^2$ collimated with aluminum honeycomb to have roughly circular fields of view, 6° FWHM (0.012 sterad) at energies above 700 eV. The window of one counter was 2.8-$\mu$ polycarbonate (Kimfol); that of the other was 4.0-$\mu$ Mylar. Both windows were coated on their inside surfaces with about 20 $\mu$g cm$^{-2}$ of colloidal carbon. The counters were of the wire-wall variety with internal veto protection. In flight, an on-board regulation system maintained the pressure of the gas (90 percent argon, 10 percent methane) constant at 1 atm. A source of Al and Ni K$\alpha$ X-rays provided in-flight gain calibrations every 35 seconds. Photographs from an on-board camera determined the look direction to within 1° throughout the flight.

In the part of the total data presented here, the scan path included no known discrete X-ray sources. The detectors viewed the Crab Nebula earlier in the flight and several sources in the Cygnus region later in the flight. A separate publication will discuss the data from these sources.

For both counters, the payload telemetered back the pulse height of each X-ray event. Figure 1 shows detailed (polycarbonate) pulse-height spectra taken during the two portions of the scan path labeled X and Y on Figure 2. Each broad peak near 200 eV follows the proportional-counter response to the counter window's X-ray bandpass below 284 eV. These low-energy pulse-height spectra are similar in all respects to spectra measured with the flight instrument but in the laboratory with X-ray beams of known energy. Thus they provide conclusive evidence for the detection of X-rays, contaminated by negligible charged-particle, $\gamma$-ray, or ultraviolet-induced background. The solid curve is the calculated response of the counter to an assumed incident X-ray spectrum $11E^{-1.4}$ photons (cm$^2$ s sterad keV)$^{-1}$. The fit above 1.5 keV is good. Below this energy there is an additional contribution to the incident intensity both in the galactic plane (region X) and near $b^{\mathrm{II}} = -50°$ (region Y).

Figure 2 shows the general features of the polycarbonate-counter results with the pulse-height data reduced to three broad bands plotted versus galactic latitude. $A$ includes X-rays below 284 eV (due to the window filtering), $B$ includes X-rays between .5 and 1.0 keV, and $C$ includes X-rays of energy greater than 1.0 keV. Also shown is $N_{\mathrm{H}}$, the columnar density of atomic hydrogen, and the zenith angle of the look direction.

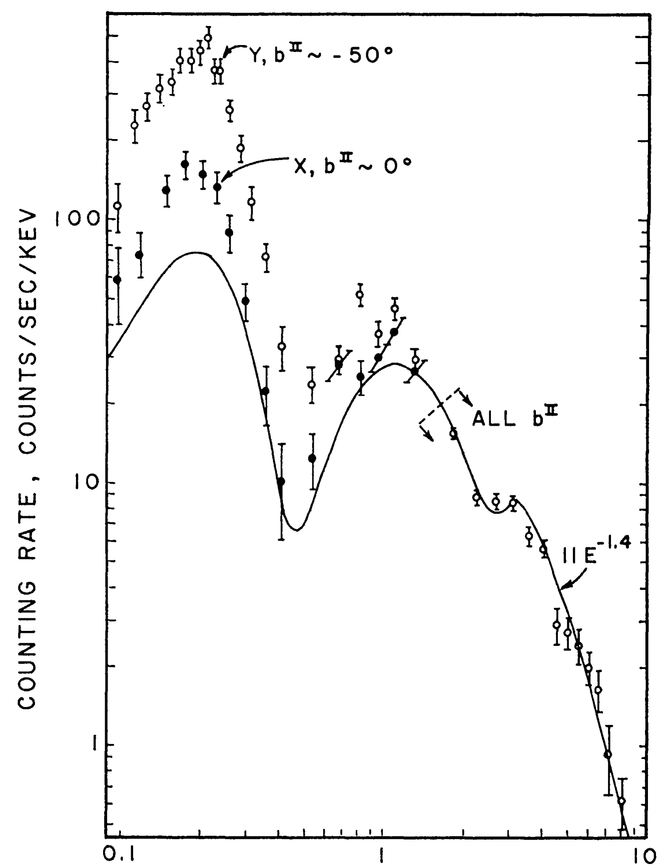


FIG. 1.—Low-energy pulse-height spectra in regions of high (Y) and low (X) galactic latitude. Above 1.5 keV, where the data fit an $E^{-1.4}$ power law, data from all $b^{\mathrm{II}}$'s have been combined. *Solid curve*, calculated detector response to the $E^{-1.4}$ power law; it includes measured window and gas efficiency, measured energy dependence of the solid angle, and the usual escape peak and counter response functions. Neither the data nor the $E^{-1.4}$ response curve includes any corrections for interstellar absorption.

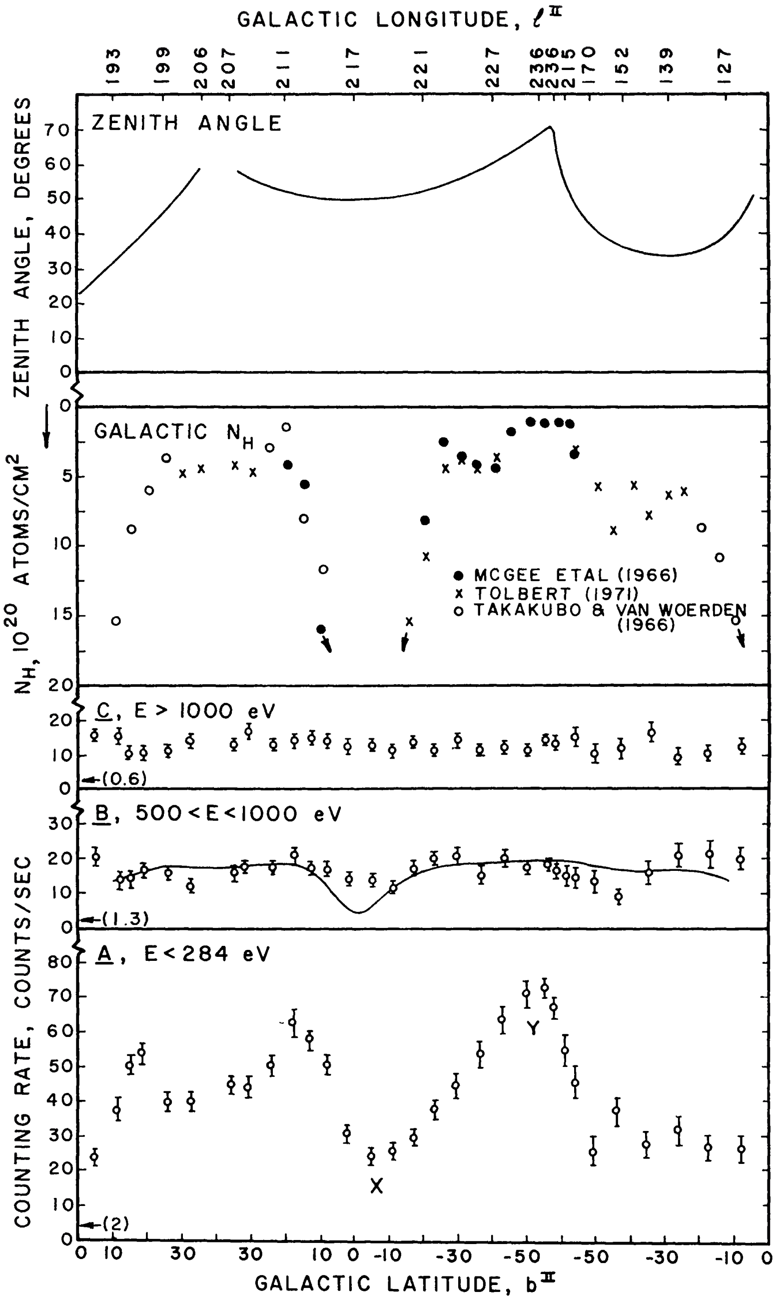


FIG. 2.—Observed counting rates in the three energy bands plotted versus the galactic coordinates of the scan path. Numbers in parentheses show the magnitude of the non-X-ray background that was subtracted. Also shown is the columnar density of atomic hydrogen (measured at 21 cm) and the zenith angle along the scan path. Dashed curve in part *B* shows the expected effect of absorption if the cross-sections of Brown and Gould (1970) are used. The curve is normalized to fit the data at high galactic latitudes. Maximum observed counting rate is about 2.2 times larger than the expected unabsorbed rate due to $11E^{-1.4}$.

Neither the $A$- nor the $B$-band intensities vary with $N_H$ as they should if all the diffuse X-rays are extragalactic and subject to photoelectric absorption by the interstellar gas. This has been noticed and reported previously, although the present measurement is the first to make possible a detailed correlation along a single scan path.

There is a gross tendency for the X-ray intensity of the $A$-band to be high when $N_H$ is small, and for the intensity to be small when $N_H$ is large. Particularly interesting is the high intensity near ($b^{II} = 18°$, $l^{II} = 212°$), an anomalously low $N_H$ region as reported in the 21-cm surveys. On the other hand, the X-ray intensity of the $A$-band is rather small at the low $N_H$ region near $b^{II} = -25°$, $l^{II} = 223°$.

We are particularly concerned with the finite and unexpectedly large $A$-band intensity in the galactic plane. Unit optical depth for photoelectric absorption near 250 eV corresponds to $N_H \simeq 2 \times 10^{20}$ atoms cm$^{-2}$ or at most several hundred parsecs. We have examined a number of solar-related phenomena, including radiation from a thermalized solar wind, in an attempt to account for our results. To date, all of the phenomena examined fail to account for the observed intensity with wide margins. These considerations will be discussed in detail in a later publication. Thomson-scattered solar X-radiation is a potentially dangerous source of background, and Hayakawa *et al.* (1970*b*) have recently considered the energy region below 284 eV. They show that the scattered intensity is sharply peaked along the horizon nearest the Sun, is a very sensitive function of the zenith angle of the Sun, and is in any event a negligible fraction of the diffuse X-ray intensity for solar zenith angles greater than 130°. Their calculations agree well with two observations, Hayakawa *et al.* (1970*a*) and Grader *et al.* (1970), wherein detectable scattered radiation would be expected. The solar zenith angle at the time of the flight reported here was 169°, and the zenith angle along the scan path is shown in Figure 2. We hesitate to attach undue significance to the fact that the highest counting rate observed occurred at the largest zenith angle. We chose the scan path to include a high-galactic-latitude region of very small $N_H$, and expected the counting rate to be large there. The chosen region happened to have a large zenith angle. Near this region, however, the counting rate correlates better with zenith angle than with $N_H$. This is cause for suspicion that local phenomena are contributing to our observed rates. We have extended the calculations of Hayakawa *et al.* (1970*a*) to conform to conditions at the time of our flight, and even extreme assumptions with regard to atmospheric density and solar X-ray flux can account for no more than $10^{-4}$ of our observed rate.

It is difficult to demonstrate clearly that measurements of this kind are free from X-rays produced by some other unspecified solar or terrestial phenomena. However, the present flight and a previous flight (Bunner *et al.* 1969) did view the same region ($b^{II} = -28°$, $l^{II} = 138°$) but at significantly different times, December 1969 and September 1968. We are now aware of some corrections that should have been applied to the 1968 data and were not. Collimator efficiency and reflections are the most important and have the effect of increasing the 0.26-keV intensities reported in Bunner *et al.* (1969) by 1.15. The 1968 and 1969 intensities then agree to within about 20 percent. We conclude that at least in this one region, there are no remarkable variations of soft X-ray intensity with time or relative position of the Sun.

Another and probably more significant observation is the consistency with which galactic-latitude variations have been reported. Despite wide variations in the reported intensity at high galactic latitudes, the plane intensity has consistently been reported small.

With some misgivings, we proceed to discuss our results assuming no X-rays of solar or terrestrial origin.

## III. DISCUSSION

Our measured $A$-band counting rate of $\sim$25 sec$^{-1}$ in the galactic plane corresponds to a photon intensity of about 120 photons (cm$^2$ s sterad keV)$^{-1}$ at 0.26 keV if the energy spectrum is broad (not a line). In evaluating this intensity we have included the measured energy dependence of the X-ray collimation. (The effective solid angle is 0.012 sterad at energies above 670 eV, 0.018 sterad at 280 eV, and 0.024 sterad at 180 eV.) If we assume that some reaction on the interstellar gas provides the source of these X-rays, the source strength must be $S_X \simeq 4 \times 10^{-16}$ eV per second per H atom. Estimates of the ionization rate necessary to maintain the temperature of the interstellar medium by energetic charged particles are in the range (4–20) $\times 10^{-16}$ (s H)$^{-1}$. With 36 eV required to produce an ion pair, the particle energy loss is $S_i \simeq (1.4\text{–}7) \times 10^{-14}$ eV (s H)$^{-1}$, which is only 35–175 times as large as the required X-ray source strength. Even relativistic electrons lose only $10^{-5}$ times as much energy via bremsstrahlung to soft X-rays as they do via ionization or collision processes. The corresponding factors for proton bremsstrahlung (either direct or via collisions with ambient electrons) are enormously less favorable, and we conclude that the soft X-rays in the galactic plane cannot be produced by energetic charged-particle bremsstrahlung unless ionization rates in the interstellar medium larger than $10^{-13}$ (s H)$^{-1}$ can be tolerated.

A similar argument applies if the detected X-rays have a line spectrum. In this case our detected rate corresponds to a (spectral) line intensity of 8.5 photons (cm$^2$ s sterad)$^{-1}$ for carbon $K$-shell fluorescent X-rays, and the source strength necessary is $4.6 \times 10^{-19}$ photons (s H)$^{-1}$. If we take the relative abundance of carbon to be $4 \times 10^{-4}$ (by number) and the $K$-fluorescent yield of carbon to be $10^{-3}$ and assume (optimistically) that carbon $K$-shell electrons are as easily knocked free as any other interstellar bound electron, the implied ionization rate is $\sim 10^{-12}$ (s H)$^{-1}$.

Silk and Steigman (1969) have considered the capture of electrons into excited states of low energy ($E \simeq 2$ MeV per nucleon) cosmic-ray nuclei of $Z > 10$. In cascading to the ground state these ions emit Doppler-broadened L$\alpha$-like radiation. These authors estimated the X-ray (1.02 keV) intensity from cosmic-ray neon to be $2 \times 10^{-1}$ (cm$^2$ s sterad)$^{-1}$. The corresponding X-radiation from cosmic-ray carbon ions would be at 368 eV, well outside the sensitive region of our detectors. While boron, with its 255-eV X-radiation, is a somewhat more abundant cosmic-ray species than is neon,the interstellar-absorption cross-section for X-rays of 255 eV is about 20 times the cross-section for 1-keV X-rays, so it is difficult to see how this process can account for the large measured intensity.

As mentioned earlier, our flight instrument also included a counter with a Mylar window. The ratio of the 280-eV X-ray transmission of the two window materials is 2.5 as measured in the laboratory. The ratio of the measured rates in flight was never less than 3 and rose to more than 5 at high galactic latitudes. Since the bandpass below 284 eV as well as the transmission at 284 eV is greater for the Kimfol than it is for the Mylar, we conclude that the incident X-rays have a higher average energy near the galactic plane than they have at high galactic latitudes. It is possible but unlikely that, as suggested by Lampton, Green, and Bowyer (1971), the incident radiation is just a carbon $K$-fluorescence line at low galactic latitudes. At high galactic latitudes we have excluded this possibility.

Both the anomalous apparent absorption of the very soft X-rays and the high intensity in the galactic plane could be explained if there were some component of the interstellar medium that elastically scattered incident intergalactic X-rays. This requires an effective scattering cross-section per hydrogen atom that is of the same order as the effective photoelectric inelastic cross-section per hydrogen atom. Thomson scattering by electrons in isolated atoms is totally inadequate. Grains of dimension $\lambda/2 \simeq 20$ Å would have a cross-section nearly $N^2$ times the Thomson cross-section, where $N$ is the number of electrons per grain, but the total amount of material available, were the grains pure carbon, falls short by a factor of $10^3$. No appreciable relief is to be found for grains of elements of higher $Z$ because then photoelectric absorption dominates over the coherent electron elastic scattering.

Silk (1970) has pointed out that emission from a hot galactic halo ($T \simeq 10^6$ ° K, $R \simeq 10$ kpc, $n_e \simeq 3 \times 10^{-3}$ cm$^{-3}$) could account for our observed intensity of soft X-rays at high galactic latitudes. If, in addition, there were cool clouds of atomic hydrogen embedded in this halo plasma, anomalous apparent absorption would of course be expected. We have not examined the stability or dynamics problems associated with this suggestion.

## IV. CONCLUSIONS

From the above we see that the intensity of soft X-rays in the galactic plane is difficult to explain on the basis of interstellar processes unless ionization rates at least as large as $10^{-13}$ (s H)$^{-1}$ can be accommodated or there exists an unlikely amount of interstellar material in the form of small (~20 Å) grains. We are left, therefore, with either numerous stellar objects such as have been suggested by Brunner *et al.* (1969), Henry *et al.* (1968), and more specifically by Ostriker, Rees, and Silk (1970), or some unsuspected solar-terrestrial phenomena.

As regards the data at moderate to high galactic latitudes, we find a significant excess over the extrapolated power law both below 284 eV and between 0.5 and 1.0 keV in agreement with our earlier report (Bunner *et al.* 1969). In neither energy region do we find the excess intensity to vary as expected with $N_H$, and so see no firm reason for interpreting it as extragalactic in origin. This view assumes, of course, that the 21-cm emission surveys provide a reliable measure of the intervening gas and that there are no wild variations in gas composition.

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