OBSERVATIONS OF SPATIAL STRUCTURE IN THE SOFT X-RAY DIFFUSE FLUX

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Received 1972 August 7

ABSTRACT

Repeated observations of a diffuse source in the region $l^{II} \sim 200°$, $b^{II} \sim +10°$ illustrate the complexity of the low-energy X-ray background. The source is not well correlated with known objects or features, and cannot be explained by geometrically simple models of diffuse emission. The measurements indicate that this emission feature, and by implication a large fraction of the $\frac{1}{4}$-keV flux observed in the galactic plane, probably originates outside the solar system.
Subject heading: X-rays

I. INTRODUCTION

Most observers agree that the measured diffuse flux of low-energy ($\sim\frac{1}{4}$-keV) X-rays is at least several times higher than expected from an extrapolation of the isotropic (and probably extragalactic) power-law spectrum observed above 2 keV (Henry *et al.* 1968, 1971; Bunner *et al.* 1971). The origins of this soft flux are uncertain. The lack of absorption by the gas in the Small Magellanic Cloud (McCammon *et al.* 1971) and the weak correlation between the $\sim\frac{1}{4}$-keV intensity and galactic neutral gas (Bowyer, Field, and Mack 1968; Bunner *et al.* 1969; Gorenstein and Tucker 1972; Davidsen *et al.* 1972; Garmire and Riegler 1972) suggest that most—perhaps all—of the flux is galactic in origin.

If one assumes that point objects are the sources, the galactic latitude dependence of the $\sim\frac{1}{4}$-keV flux suggests that the objects are fairly numerous and distributed more broadly about the galactic plane than is the interstellar gas (Bunner *et al.* 1969). At present, no established point-source mechanism is known. (See, however, Strittmatter, Brecher, and Burbidge 1972.) As more detailed and sensitive observations are made, the complexity of the spatial structure at $\sim\frac{1}{4}$-keV argues against any simple schematic representation of the data. Some of the flux must originate in fairly distant objects like the Cygnus Loop (Gorenstein *et al.* 1971), the Vela supernova remnant, and the Lupus Loop (Palmieri *et al.* 1971, 1972). Some of the flux must originate in more local objects like the North Polar Spur which the Wisconsin group has found to be associated with an extended region of $\sim\frac{1}{4}$-keV emission (Bunner *et al.* 1972; Shklovski and Sheffer 1971). And, we emphasize, it remains to be shown that some sizable fraction of the flux does not originate within a few hundred a.u. of the Earth.

We present here detailed observations of the soft X-ray flux for a region centered on $l^{II} \sim 205°$, $b^{II} \sim 15°$. The data show an extended region of enhanced emission (seen also by Bunner *et al.* 1971; Davidsen *et al.* 1972; and Yentis *et al.* 1971) which is not well correlated with any known astronomical objects or features.

II. EXPERIMENTAL DETAILS

The sounding-rocket payload, launched 1971 March 20 at 05:30 UT from White Sands, New Mexico, contained three sets of X-ray detectors. One of these used a

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450 cm² 255 μg cm⁻² thick polycarbonate (Kimfol) window which provided a fairly narrow passband below the carbon K-edge (measured transmissions of 45 percent at 0.28 keV, 8.9 percent at 0.18 keV). Another counter used Formvar to achieve a broader passband (73 percent at 0.28 keV, 41 percent at 0.18 keV) with a net area of 276 cm². The third counter window was 104 cm² of Formvar coated with fine (300–500 Å) boron powder (0.15 ± 0.07 percent at 0.28 keV, 17.5 ± 1.2 percent at 0.18 keV); thus this counter had a well-defined passband below the boron K-edge ($E = 0.188$ keV).

All of these windows included opaque coatings to eliminate significant ultraviolet sensitivity. The multilayer construction of the detectors provided excellent non–X-ray background rejection as well as a monitor of low-energy electron contamination (see discussion of McCammon *et al.* 1971). Only the top layer of the Formvar-window counter showed any evidence for such electrons. A mild extrapolation of our observed electron spectrum to lower energies implies that at most 5 percent of the $\frac{1}{4}$-keV events in this counter could be due to low-energy charged particles. Higher-energy data from the top layer of this counter were not used in the analysis.

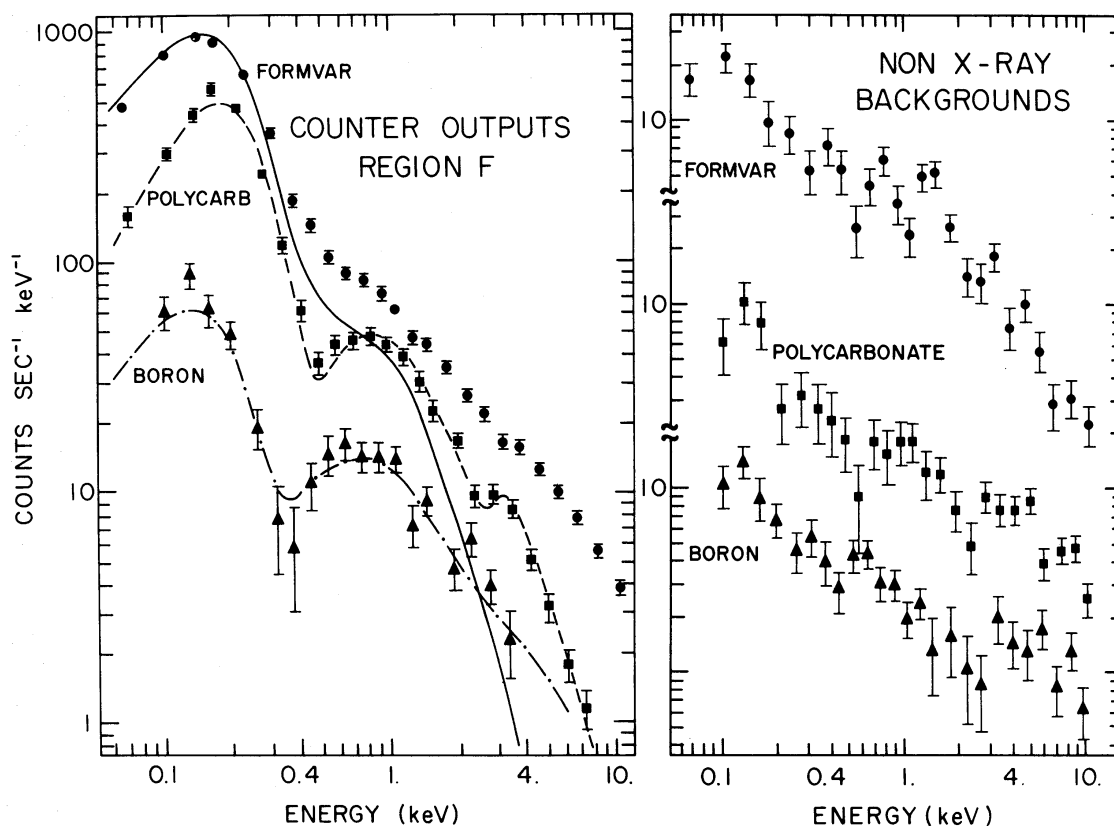Good-quality data were also available above 2 keV, thereby permitting fits to the

FIG. 1.—Observed pulse-height spectra from region F (see fig. 3i). Data are averages from 27 s of observation and have been corrected for cosmic-ray background and small (< 10 percent) dead-time effects. The non–X-ray backgrounds are average spectra observed when looking at the Earth (rocket altitude ~100 km) or at the closed payload door; door-closed and Earth-looking backgrounds agreed within their individual statistical uncertainties. The lines show the calculated responses to an incident spectrum $dN/dE = 11E^{-1.3}$ (attenuated by $N_H = 4 \times 10^{20}$ H cm⁻²) + 160 exp $(-E/0.32)/E$ (with no interstellar attenuation) photons (cm² s sterad keV)⁻¹. The increasing difference between the observed and predicted spectra for the Formvar counter at higher energies is presumably due to soft electrons, since no such difference was observed in the lower layer of this counter.

power-law diffuse flux and spectrum of the Crab Nebula. Such fits add confidence to the determination of absolute fluxes and confirm the proper operation of the counters. Figure 1 shows some of our observed pulse-height spectra. We emphasize the well-determined and very small background and close agreement between the observed and predicted pulse-height spectra, including the definite spectral turnover below 0.25 keV due to absorption in the polycarbonate and Formvar windows.

III. COMPARISON WITH A PREVIOUS OBSERVATION

Bunner *et al.* (1971) discussed in some detail the large flux of $\frac{1}{4}$-keV X-rays in the plane of the Galaxy. Because of heavy absorption by the interstellar gas, these X-rays must originate within several hundred parsecs of the Sun. Observationally, in fact, we cannot exclude the possibility that a large fraction of the flux originates within the solar system. In this case, we might expect the spatial structure and intensity to vary with time or solar and geophysical conditions.

For this reason, a portion of our 1971 March flight retraced part of the scan path of our 1969 December flight. Both flights included the same instrumentation except that the polycarbonate window for the earlier flight was thicker: $\sim 335~\mu g~cm^{-2}$. The conditions at launch were quite different: ecliptic longitude of the Sun 253° (1969) versus 359° (1971); solar zenith angle 169° (1969) versus 142° (1971); altitude of rocket ~ 140 km (1969) versus 150–190 km (1971); zenith angle for $l^{II} = 205°$, $b^{II} = 35°$:59° (1969) versus 23° (1971). In spite of these differences, agreement between the two sets of observations is excellent. As figure 2 shows, the two $\frac{1}{4}$-keV rates show the same
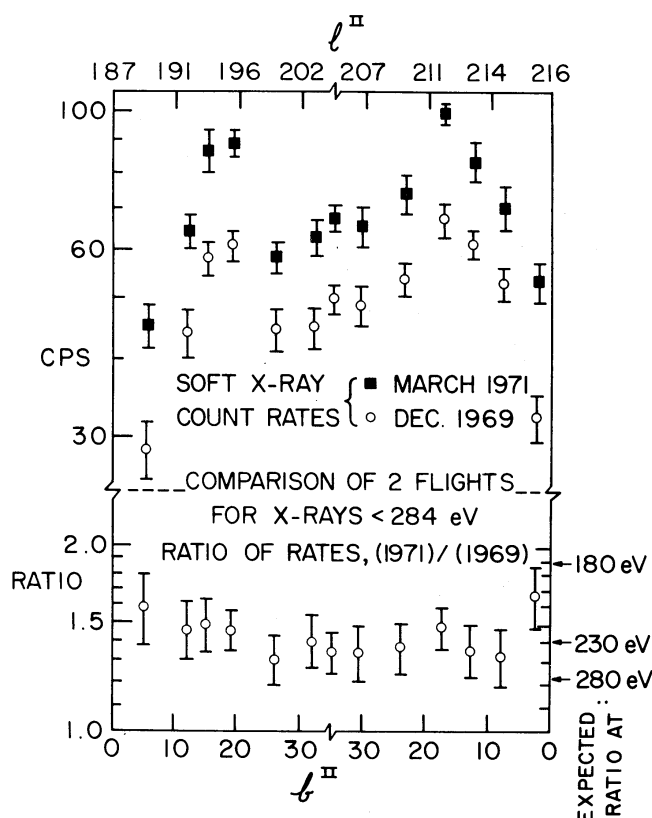

FIG. 2.—Comparison of counting rates for two observations of the same scan path. Data have been corrected for non–X-ray background (2 cps, 1969; 5 cps, 1971) and atmospheric transmission >84%, 1969; >89%, 1971). "Expected ratio" refers to the ratio of window transmissions.

spatial structure, and their relative intensities are completely consistent with the slightly different window thicknesses and a soft spectrum of characteristic energy ~ 0.23 keV. At the 3 σ level, this agreement implies that over a 15-month interval the intensity changed by less than ± 30 percent.

We believe this observation provides strong though admittedly not conclusive evidence that most of these X-rays do not originate within the solar system or the Earth's upper atmosphere. To examine further the question of their origin, we turn now to a discussion of the spatial structure of the soft flux seen during the 1971 flight.

IV. SPATIAL STRUCTURE OF SOFT X-RAYS NEAR THE GALACTIC ANTICENTER

In figure 3 we show the galactic-coordinate dependence of four soft X-ray counting rates from the 1971 observation. These plots display the net rates corrected for background (see figure legend), atmospheric attenuation (< 15 percent), and dead-time effects (< 10 percent) averaged over $\sim \frac{1}{2}$ to 1 angular resolution element.

The known point X-ray sources on our scan path (IC 443, 2U 0613+09, NGC 1275, and the Crab; Giacconi *et al.* 1972) give detectable rates only above 0.5 keV. The low-energy measurements show a quite different spatial structure, and in particular there appear to be three regions of enhanced emission.

The collimator response is such that two of these regions at (l^{II}, b^{II}) of $(195°, +20°)$ and $(205°, +0°)$ might be point sources. The third region, centered on $(205°, +15°)$, is clearly extended. These three areas might be separate emission volumes or they might be but parts of one large region of enhanced emission. Preliminary analysis of a more complete scan of this area on 1972 February 18 favors the latter interpretation.

A general comparison of our soft X-ray rates with 21-cm emission studies of the interstellar hydrogen (Daltabuit and Meyer 1972, and references therein; Venugopal and Shuter 1970) shows at best a weak and highly variable inverse correlation between rates and absorbing material. For example, while the lowest value for N_H on our scan path, 2×10^{20} H cm^{-2}, occurs at a high rate point $(212°, +18°)$, equally high X-ray rates occur at $(200°, +10°)$ where $N_H = 10^{21}$, and at $(195°, +20°)$ where $N_H = 7 \times 10^{20}$. Aside from the regions of enhanced emission, the boron rate is nearly independent of look direction.

In an effort to understand better these spatial intensity variations and the dependence of the X-ray spectrum on position on the sky, we have concentrated on eight sections of the scan path (see fig. 3i). The data for these sections are summarized in table 1. The last four areas refer to the region of enhanced emission, while the first four display the general galactic latitude dependence of the "normal" region. Data given in parentheses have been corrected for non–X-ray background and atmospheric attenuation. For all other tabulated rates, we have also subtracted the contribution from the extrapolated (assumed extragalactic) power-law spectrum attenuated by the appropriate amount of intervening gas. The ratios tabulated in the right-hand columns reflect the "softness" of the data; i.e., the larger any one of the ratios is, the steeper the spectrum.

Referring first to the "normal" region below the carbon K-edge, both the boron/polycarbonate and Formvar/polycarbonate ratios suggest a softer spectrum in the plane. That is, the intensity of the longest wavelengths observed (~ 70 Å) was rather insensitive to look direction, while the ~ 50 Å flux (polycarbonate) decreased significantly between high and low latitudes. On the other hand, the $\frac{1}{2}$- to 1-keV flux is either constant (if we assume no power-law component), or a factor of two larger in the plane (if we assume that the power law may be extrapolated down to $\sim \frac{1}{2}$ keV).

We believe, however, that none of the available data, presented here, or elsewhere, permit general conclusions concerning the hardness or softness of the low-energy flux in the plane at all galactic longitudes. For example, the spectrum at point C $(215°, 2°)$
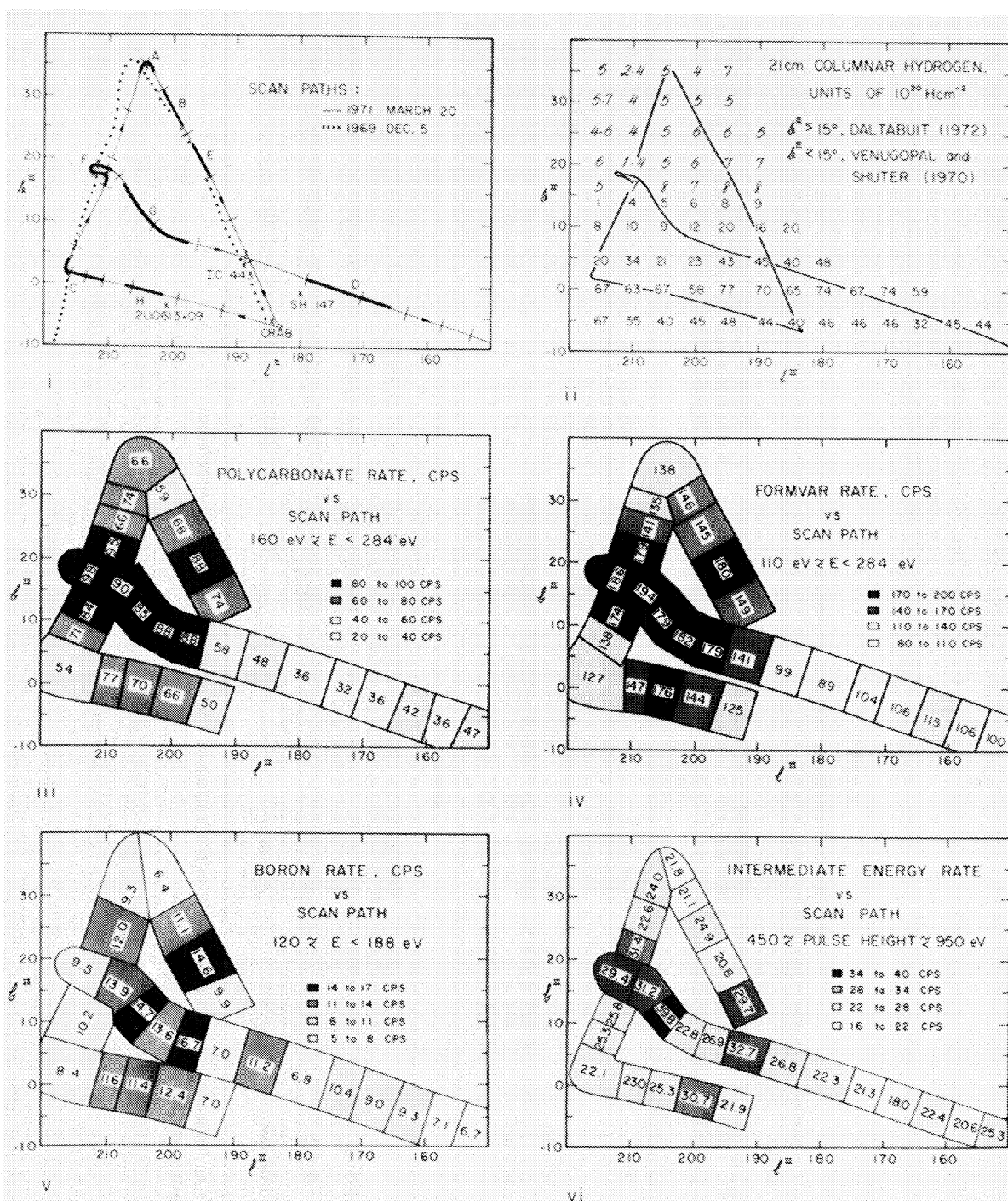
Fig. 3.—Scan data for 1971 flight. (i) The scan path in galactic coordinates for 1971 flight showing regions A through H listed in table 1. Hash marks indicate 5-s intervals. (ii) Value of $N(H)$ from 21-cm surveys (Daltabuit and Meyer 1972; Venugopal and Shuter 1970). (iii) Net counting rates in cps for polycarbonate counter, X-ray energies < 284 eV, background correction 5 cps, statistical precision ± 5 cps, collimator FWHM $8°$. (iv) Net rates for Formvar counter, $E < 284$ eV, background correction 5 cps, statistical precision ± 7 cps, FWHM $8°$. (v) Net rates for boron counter, $E < 188$ eV, background correction 2.7 cps, statistical precision ± 2.0 cps, FWHM $9°$. (vi) Net rates for $\frac{1}{2}$ to 1 keV pulse-heights from boron and polycarbonate window counters, background 3 cps, statistics ± 4 cps, FWHM $6°$. For plots (iii)–(vi), the widths of the boxes denote the collimator FWHM.

TABLE 1
Net Rates for Eight Selected Areas

Region	l^{II}, b^{II}	$N(\mathrm{H})$ $\left(\times 10^{-20}\ \frac{\mathrm{H}}{\mathrm{cm}^{-2}}\right)$	Boron Rate (cps)	Formvar Rate (cps)	Polycarbonate Rate (cps)	$\frac{1}{2}$–1 keV (cps)	$\dfrac{\text{Boron}}{\text{Polycarbonate}}$	$\dfrac{\text{Formvar}}{\text{Polycarbonate}}$	$\dfrac{\text{Polycarbonate}}{\frac{1}{2}\text{–1 keV}}$
					"Normal"				
A.......	205, +34	4–5	8.5 ± 1.2 (8.7 ± 1.2)	121 ± 5 (124 ± 4)	61 ± 3 (63.5 ± 2.7)	8.5 ± 1.8 (21.2 ± 1.7)	0.14 ± 0.02 (0.14 ± 0.02)	2.0 ± 0.1 (2.0 ± 0.1)	7.2 ± 1.6 (3.0 ± 0.3)
B.......	200, +28	7	9.8 ± 1.4 (10.0 ± 1.4)	111 ± 4 (113 ± 4)	47 ± 3 (49.1 ± 2.7)	9.4 ± 3 (21.4 ± 2.9)	0.21 ± 0.02 (0.20 ± 0.02)	2.4 ± 0.1 (2.3 ± 0.1)	5.0 ± 1.6 (2.3 ± 0.3)
C.......	215, +2	50–100	8.3 ± 1.0 (8.3 ± 1.0)	115 ± 3 (115 ± 3.2)	49 ± 2.2 (49.4 ± 2.2)	19.2 ± 1.9 (21.8 ± 1.4)	0.17 ± 0.02	2.4 ± 0.1	2.5 ± 0.3 (2.3 ± 0.2)
D.......	173, +0	100–140	9.1 ± 1.2 (9.1 ± 1.2)	91 ± 3.5 (91 ± 3.5)	33 ± 2.1 (33 ± 2.1)	19.2 ± 1.9 (20.7 ± 1.8)	0.27 ± 0.04	2.8 ± 0.2	1.7 ± 0.2 (1.6 ± 0.2)
					"Enhanced"				
E.......	192, +20	7	13.7 ± 2.4 (13.9 ± 2.4)	169 ± 8 (171 ± 8)	81 ± 5.5 (82.8 ± 5.5)	9.6 ± 3.0 (21.6 ± 2.9)	0.17 ± 0.03	2.1 ± 0.2	8.4 ± 2.7 (3.8 ± 0.6)
F.......	212, +18	1.5–4	9.6 ± 0.8 (10.0 ± 0.8)	157 ± 6 (167 ± 3)	82 ± 4 (88.6 ± 2.0)	14.8 ± 1.3 (29.6 ± 1.2)	0.12 ± 0.01	1.9 ± 0.1	5.5 ± 0.6 (3.0 ± 0.2)
G.......	203, +10	8–12	14.9 ± 1.5 (15.1 ± 1.5)	166 ± 5 (167 ± 5)	79 ± 3.3 (80.3 ± 3.3)	15.9 ± 2.1 (27.9 ± 2.0)	0.19 ± 0.02	2.1 ± 0.1	5.0 ± 0.7 (2.9 ± 0.2)
H.......	205, +0	80–100	8.9 ± 1.7 (8.9 ± 1.7)	156 ± 6 (156 ± 6)	69 ± 4.5 (69 ± 4.5)	*	0.13 ± 0.03	2.3 ± 0.2	*

Note.—Numbers in parentheses have not been corrected for contribution of the isotropic power-law spectrum.
* Deleted due to possible contamination by 2U 0613+09.

in the plane is more similar to the "hard" point B (200°, 28°) than to the "soft" point D (173°, 0°) in the plane; and the "hardest" spectrum seen on our 1969 flight (Bunner *et al.* 1971) occurred just below the plane at (218°, −2°). Thus, the data show significant spatial structure in galactic longitude as well as latitude. A full interpretation of the flux cannot ignore this complex structure.

V. THE ENHANCED EMISSION REGION

The E-F-G-H region of enhanced emission (centered on 205°, 15°) has several interesting features. The Formvar and polycarbonate rates are fairly constant for all four points, allowing for the fact that point H is probably near the edge of the extended emission region. The boron rate is generally larger and more variable than in the "normal region." In view of the uncertainties involved in removing (or not removing) the power-law contribution to the $\frac{1}{2}$–1 keV data, it is not clear whether this "enhanced emission region," which shows up so obviously for $\lambda > 44$ Å, shows up at all for $\lambda \lesssim 25$ Å.

As figure 3 shows, the region is at least 10°–20° in extent, and the quantitative correlation between X-ray rate and total columnar density of neutral hydrogen, N_H, is poor. All the rates for $E < 284$ eV show a sharp decrease as the payload scanned from (200°, 10°) to (185°, 5°). This dropoff could indicate the edge of the emitting volume or the edge of an intervening cloud of gas or dust. The rate decrease does roughly correlate with one other astronomical feature, a ridge in N_H (Venugopal and Shuter 1970). For example, N_H increases from 2.3×10^{21} at (200°, 5°) to 4.3×10^{21} H cm^{-2} at (195°, 5°). (Note that at $\frac{1}{4}$ keV, one optical depth corresponds to 0.25×10^{21} H cm^{-2}.) While the distance to the gas responsible for this feature is unknown, there can be no doubt that it is well outside the solar system.

The intensity in the enhanced region exceeds that in the normal region by about 70 photons (cm^2 s sterad keV)$^{-1}$ at 0.25 keV and has a spectrum roughly consistent with that expected from a gas at ~ 3 million degrees. Assuming the source to be optically thin and the radiation to be unattenuated by intervening neutral gas, we find the required emission measure, $\int N_e^2 dR$, to be about 6×10^{15} cm^{-5} = 0.002 pc cm^{-6}. Here we have used the emissivities of Tucker and Koren (1971). The magnitude of this emission measure is totally inconsistent with a localized hot ionized region in pressure equilibrium with the interstellar medium. (Pressure equilibrium at 3 million degrees implies $N_e \sim 10^{-5}$ cm^{-3}, whence R, to provide the emission measure, would have to be ~ 20 Mpc.) We are led to assume, therefore, that the region is expanding and to estimate the expansion velocity to be in the range 300–600 km s^{-1}.

Since our two observations, 15 months apart, show no angular motion greater than about 5°, we can set a modest but nonetheless significant lower limit of 800–1500 a.u. for the distance to the expanding emitting region.

VI. SUMMARY

We have presented low-background observations of the diffuse X-ray flux in three broad energy bands, $\sim 100 < E < 188$ eV, $\sim 120 < E < 284$ eV, and $\sim 0.5 < E < \sim 1.0$ keV, for a region of the sky centered on $l^{II} = 200°$, $b^{II} = 10°$. We observed parts of this region 15 months earlier, and agreement between the two sets of measurements is excellent. These observations provide fairly strong evidence that at least the intensity feature we observe is not solar or terrestrial in origin, but only weak evidence that the general featureless background is not of local origin.

One edge of the intensity feature where the intensity decreases by a factor of 2 coincides with a factor-of-2 increase in the columnar density of interstellar gas. The total amount of gas involved corresponds to greater than 7 optical depths at $\frac{1}{4}$ keV;

thus the rate decrease in no way suggests an extragalactic origin. If the X-ray feature represents attenuation by the intervening gas feature, the emitting volume must be at least ~ 100 pc distant. If the X-ray feature simply represents the edge of the emitting volume, simple considerations of emission measure and expansion velocity place the source region at a distance > 1000 a.u.

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