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Extended Regions of Soft X-Ray Emission and Background Spectrum at Southern Latitudes

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A survey of Southern galactic hemisphere was made with a soft X-ray rocket-borne telescope launched on October 27, 1976 from the equatorial station, Thumba (S. India). Three extended regions of diffuse soft X-ray emission in the C-band (0.15–0.5 keV) and M-bands (0.5–1.5 keV) were detected and appear to be coincident with the regions of very low neutral hydrogen column density. Plasma temperatures of a few million degrees are required to explain the X-ray emission from these regions.

INTRODUCTION

The brightness distribution of soft X-ray background has been studied by various investigators (Davidsen *et al.* 1972; Williamson *et al.* 1974, de Korte *et al.* 1976; Burstein *et al.* 1977; Levine *et al.* 1977; Long *et al.* 1977; Hayakawa *et al.* 1978; Iwanami *et al.* 1979; Fried *et al.* 1980). The sky maps obtained in various surveys show many complex features and the energy spectrum of soft X-rays also seems to vary quite significantly in different directions of the galaxy. While gross features observed in different experiments are in fair agreement, detailed comparisons do reveal differences.

The diffuse X-ray background at photon energies above 1 keV is found to be highly isotropic and thus is considered to be of extragalactic origin (Schwartz 1978, Marshall *et al.* 1980). The distribution of the softer component below 1 keV is highly nonuniform and patchy; also the observed variation of X-ray flux with galactic latitude is inconsistent with that expected from the absorption of hydrogen and helium distribution in the interstellar medium. The existence of a large flux in the galactic plane and the absence of absorption in the Magellanic clouds and by *M*31 (Henry *et al.* 1968; McCammon *et al.* 1971; Long *et al.* 1976; McCammon *et al.* 1976) indicate that a large fraction of sub-keV diffuse background radiation is galactic in origin and is believed to be produced by the thermal emission of a hot interstellar gas at 10^6 °K.

The brightness distribution maps show that the soft X-ray flux is enhanced in the Low N_H regions and also correlates with the radio features such as galactic loops. A number of soft X-ray sources like Vela SNR, Cygnus loop, Capella, SS Cygni, YZ Canis Minoris, Her X-1, MX 1313+29 and MX 2140−60 have been discovered in previous surveys. Apart from these sources, some special extended regions of enhanced X-ray emission in the North Polar Spur and "hot spots" in Gemini-Monoceros and Eridanus have been identified and are suggested to be due to thermal emission of merged and re-heated supernova remnants (Cox and Smith, 1974).

In this paper we report the observation of extended regions of enhanced X-ray emission in the constellation of Telescopium-Tucanae, Fornax and Eridanus in the southern galactic hemisphere. The data were obtained from a rocket experiment conducted from Thumba Equatorial Rocket Launching Station (latitude 8.5°N, longitude 76.9°E).

EXPERIMENT AND DATA ANALYSIS

The soft X-rays were observed with two multi-anode double layered wire-wall proportional counters. Each counter had an effective area of about 210 cm^2 and depth of 5 cm filled with pure methane at one atmospheric pressure and sealed with an entrance window of 6μ thick polypropylene film coated with 60 $\mu g\ \text{cm}^{-2}$ carbon. The two layers are operated in anti-coincidence to reduce the detector background. The field of view of the detector is restricted to $8° \times 8°$ FWHM by slat collimators which were canted 10° above the rocket equatorial plane. Figure 1 shows the detection efficiency and resolution of the two detectors as a function of energy, energy resolution being measured at 0.28, 1.5 and 5.96 keV. The aspect information during the flight was provided by a crossed pair of flux gate magnetometers mounted on the instrument deck.

The experiment was launched aboard a Centaur rocket on October 27, 1976 at 1627 UT. This experiment is the first of the series of rocket flights carried out to survey soft X-rays, from geomagnetic equator. The launch time and the scan path was chosen such that the field of view of the detector crossed the Eridanus region.

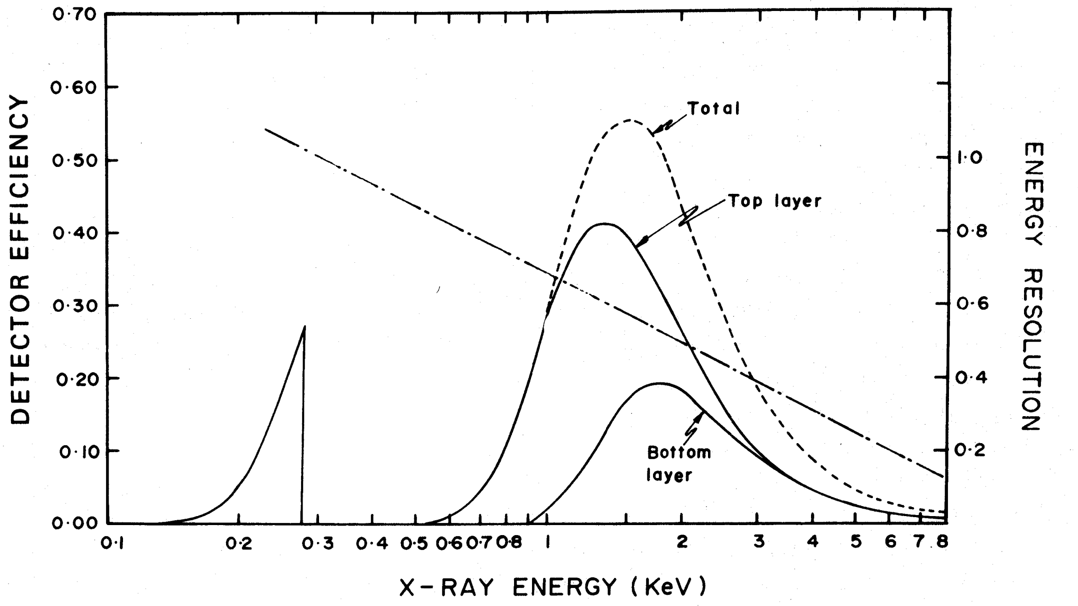

FIGURE 1 Detection efficiency of the proportional counter (solid and dash–dash curves) and its energy resolution (straight line) as a function of X-ray photon energy.

The spin rate of the rocket stabilized at 2.815 s^{-1}. A narrow band in the sky was scanned due to null precession of the rocket. The inflight performance of the counters was monitored by onboard calibration with 5.96 keV X-ray line from an Fe^{55} radioactive source. No gain shift of the detectors was observed during the flight.

The quality of soft X-ray data depends upon the level of contamination due to ultraviolet transmission and the charged particle background. In our experiment the contamination due to ultraviolet radiation is totally absent since the window is coated with thick layer of carbon. Among charged particles, the contamination due to low energy electrons is the major source of error in soft X-ray measurements. At mid-latitudes such a contamination is very large even at rocket altitude of about 150 km (Naranan *et al.* 1974), however, the precipitation of low energy magnetospheric electrons is negligible at geomagnetic equator (Seward 1974). Non X-ray background and the internal detector background in our experiment were less than 20% of the observed counting rate in 0.1–1.5 keV energy band. Only that part of the data for which the atmospheric correction is less than 10% has been included in the present analysis.

The counts obtained in successive spins were superposed in bins of 4.5° in azimuth and the results are shown in Figure 2 for the three pulse-height intervals corresponding to X-ray energies 0.15–0.5 keV (C-band); 0.5–1.5 keV (M-band) and 1.5–4.5 keV (H-band). The detection efficiencies in Figure 1, show that the counting rate in the C-band is dominated by X-rays in the energy range 160–280 eV. The dip in the data at 270°–360° in azimuth corresponds to the earth looking direction. Four regions of excess emission are marked in the figure. The region 1 corresponds to the galactic center region and is visible only at energies above 1.5 keV and is completely absent in C-band, while the other three regions dominate only the C-band.

BRIGHTNESS DISTRIBUTION AND LATITUDE DEPENDENCE

The spatial distributions of counts summed from both the proportional counters along the scan path, in the C and M bands (0.15–0.5 keV, 0.5–1.5 keV) in galactic coordinates are shown in Figure 3, with darker regions indicating higher counting rate. In order to get meaningful statistics the data were lumped into 4.5° × 8° bins, the 4.5° being in the rocket azimuth. The data from northern latitudes which correspond to earth looking direction of the rocket are not shown in the plot. The maps cover certain areas in the galactic sphere which have not been studied in detail in the past surveys. Except for a single significant peak coincident with the position of MX 2140-60, identified with a southern galactic cluster (Singh *et al.* 1981b) there is no evidence for any other point source in our data.

REGIONS OF ENHANCED EMISSION

Three broad regions of significant emission are visible in the C-band as shown in Figure 3. The intensity enhancements in these regions are more than three standard

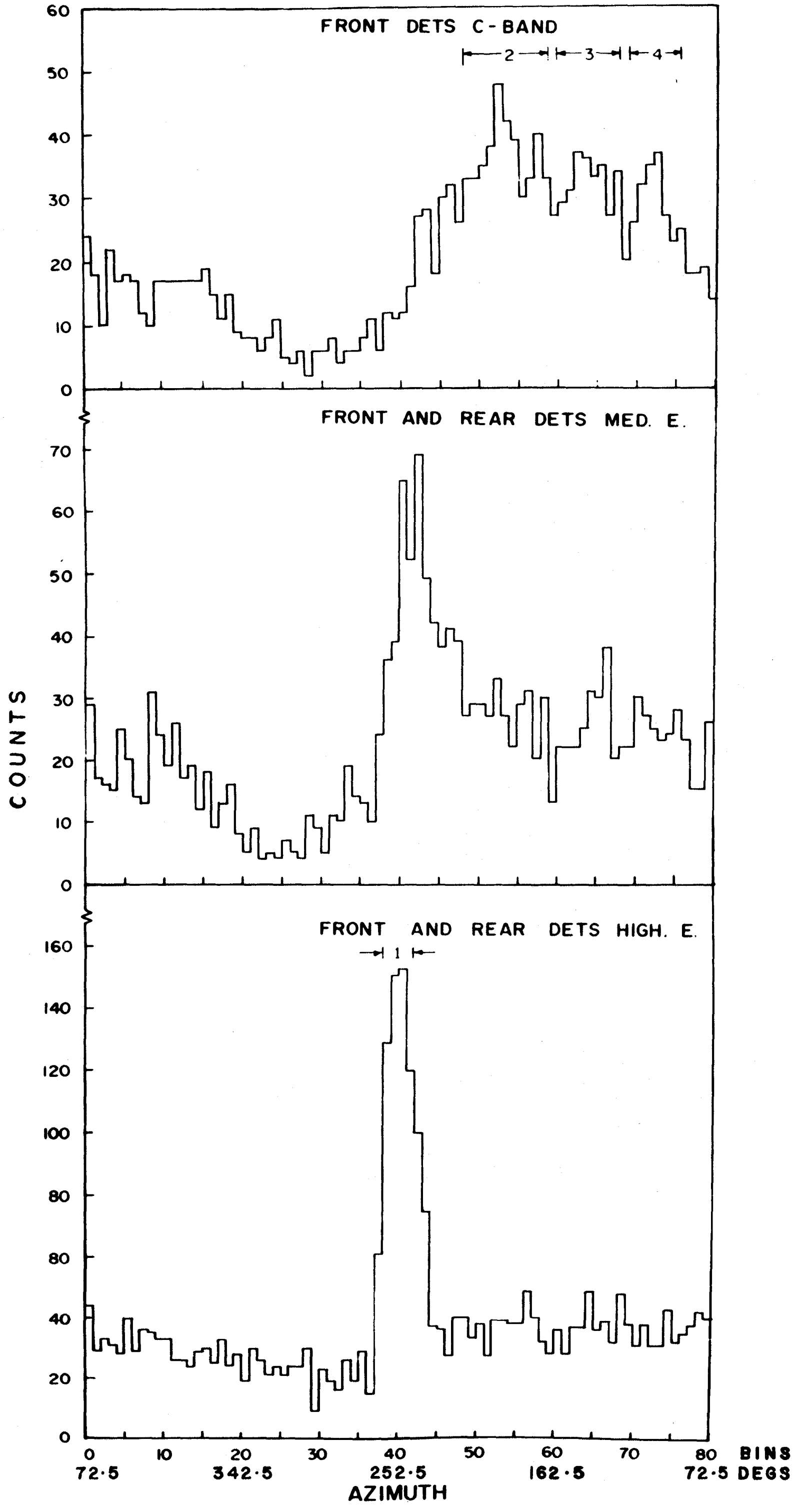

FIGURE 2 Total number of X-ray counts detected during the flight plotted against the rocket azimuth. Counts in three energy bands: C-band (0.15–0.5 keV), M-band (0.5–1.5 keV) and H-band (1.5–4.5 keV) (top, middle and bottom) are shown separately. Each azimuthal bin is 4.5° wide. Regions marked 1, 2, 3 and 4 are in the galactic center region, Telescopium-Tucanae, Fornax and Eridanus respectively.

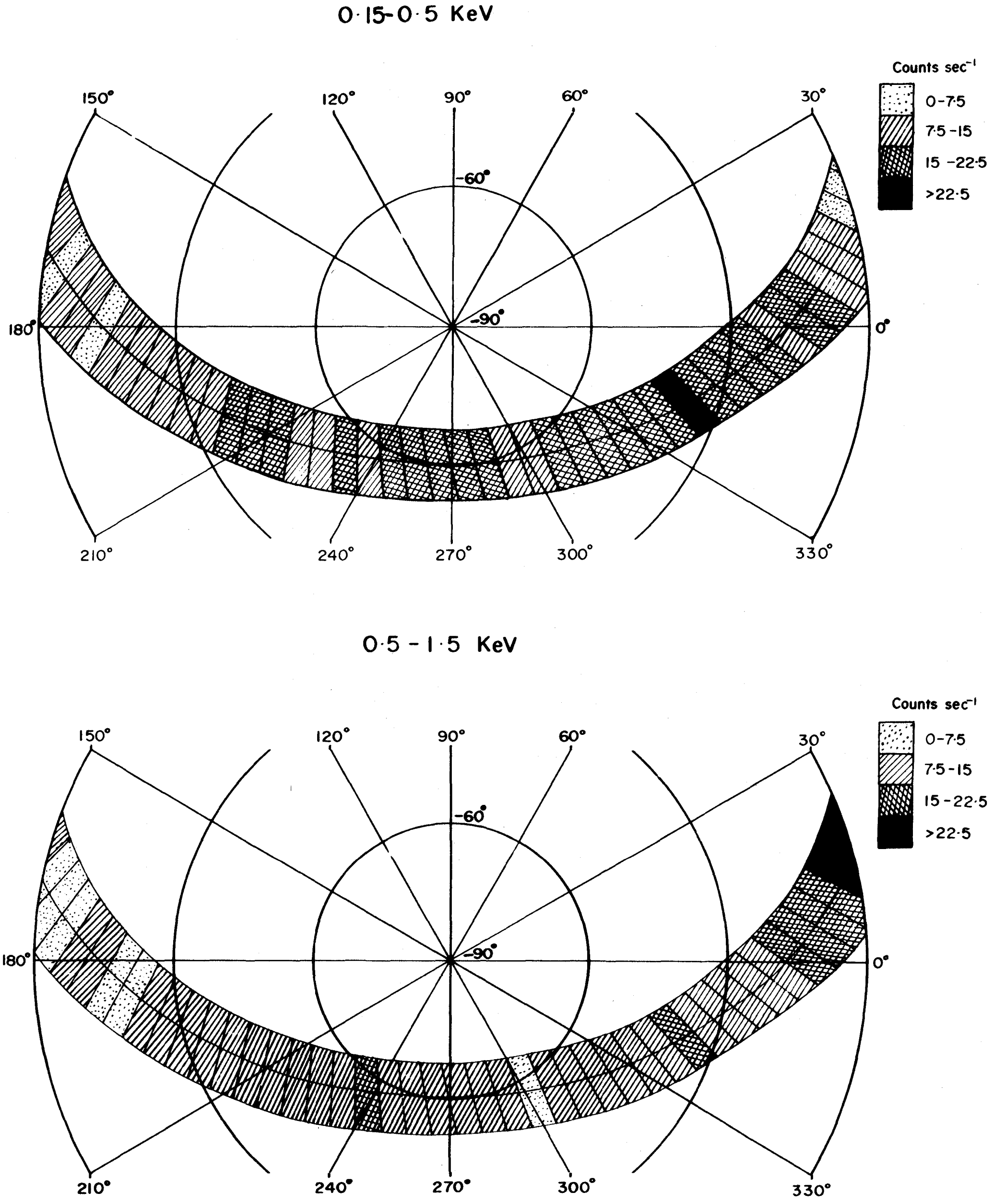

FIGURE 3 Count rates in C and M-bands shown along the scan path in galactic coordinates.

deviations over the surrounding regions exclusive of the point source. The regions are:

A:	$310° < l < 345°$,	$-55° < b < -25°$
B:	$240° < l < 290°$,	$-65° < b < -55°$
C:	$200° < l < 215°$,	$-45° < b < -35°$

These regions are located in the constellations Telescopium-Tucanae, Fornax and Eridanus respectively.

The enhancement in Telescopium-Tucanae (region A) is centered around $l = 330°$, $b = -50°$ and is prominent both in C and M bands. It also appeared as a region of excess emission in the Wisconsin survey which partly scanned this area (Sanders *et al.*, 1977). The region is coincident with the direction of low N_H feature extending from $l = 310°$, $b = 45°$ to $l = 340°$, $b = 70°$ (Daltabuit and Meyer 1972).

The enhancement in Fornax (B) is centered around $l = 250°$ and $b = 60°$. This region is part of the very large region of soft X-ray excess, different parts of which have been observed in the earlier experiments of Bunner *et al.* 1971, Sanders *et al.* 1977 and Long *et al.* 1977.

The soft X-ray excess in the Eridanus region (C) is centered around the hot spot $l = 205°$, $b = 40°$ and is coincident with the excess emission reported by Naranan *et al.* 1976, and Long *et al.* 1977.

Present data indicate that the enhanced X-ray emission is mainly concentrated in the C-band (0.15–0.5 keV) for all the regions. Although the regions A and B do coincide with the low N_H ($<3 \times 10^{20}$ atoms cm^{-2}) features, the C-band excess is entirely galactic as discussed later.

LATITUDE DEPENDENCE

The latitude dependence of the soft diffuse background can be inferred from the correlation map of C-band data with N_H column density in different directions as obtained from 21 cm radio observations (Daltabuit and Meyer 1972). The data shown in Figure 4 indicate that there is no definite correlation between the C-band brightness and N_H. The plateau in the 0.15–0.5 X-ray emission in the low N_H ranges of $(1\text{–}6) \times 10^{20}$ N_H cm^{-2} as seen in our data indicates that there is no gross tendency of increase in the C-band intensity with latitude contrary to the observations in northern latitude (de Korte 1975). The comparison of the spectra of region D, near the galactic anticenter shown in Figure 5, for which no enhancement was seen in C-band, with that obtained for the galactic center region obtained in this experiment (Singh *et al.* 1981a) indicates that the soft X-ray flux values show a remarkable variation in the center and anti-center regions. The variation of the hardness ratio with N_H (Figure 4) shows that the X-ray spectra are very soft in the region of low N_H.

X-RAY SPECTRA

The energy spectra for the three high galactic latitude regions of enhanced emission corresponding to Telescopium-Tucanae, Fornax and Eridanus are shown in Figure 5 along with another region (marked D) near the galactic plane in the anti-center direction ($l = 160°\text{–}190°$, $b = -20°$ to $10°$), which shows no enhancement. Since our discussion concerns the spectrum and isolation of the galactic component, and the data-energy bandwidth is small above 1 keV, we have estimated the extragalactic contribution in our data by spectral fitting of the high energy points in all the regions with following spectral forms for the extragalactic diffuse component.

$$\frac{dN}{dE} = A_1\, E^{-1.4} \text{ photons cm}^{-2}\text{ s}^{-1}\text{ sr}^{-1}\text{ keV}^{-1}$$

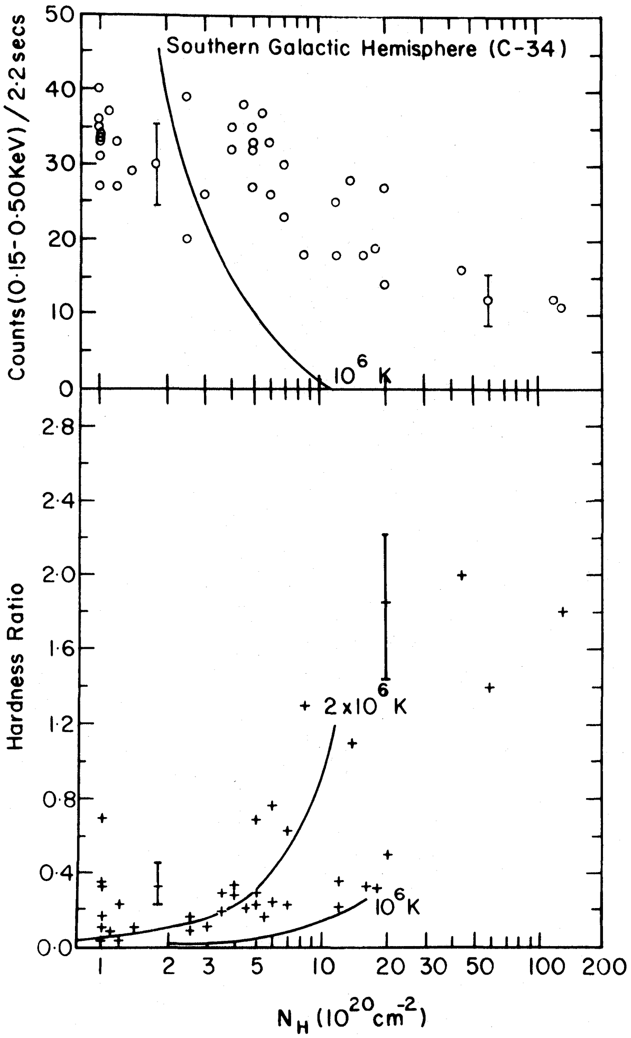

FIGURE 4 C-band counts versus the neutral hydrogen column density N_H and the Hardness ratio (M-band counts/C-band counts) versus N_H. The curves shown are the predicted values calculated from a hot, thin plasma (Kato 1976) at temperatures of 10^6 K and 2×10^6 K.

or

$$\frac{dN}{dE} = A_2\, E^{-1} \cdot g(E) \cdot \exp(-E/40) \text{ photons cm}^{-2}\text{ s}^{-1}\text{ sr}^{-1}\text{ keV}^{-1}$$

where $g(E)$ is the gaunt factor for free-free emission from a hot plasma. In each plot, the curve shown by I_{eg} is the result of convolving the extragalactic diffuse X-ray spectrum with the detector efficiency and resolution function and is clearly seen to fit only the high energy data between 1–4 keV. However the measured spectra give acceptable fits to both power law with index = 1.4, (Schwartz 1978) and exponential $kT = 40$ keV (Marshall *et al.* 1980) spectra. The acceptance criterion for the range of parameters at the confidence level of 90% is determined by the reduced χ^2 test as suggested by Lampton *et al.* 1976, keeping the neutral hydrogen density as a free parameter. The range of neutral hydrogen column density as estimated from optimum choice of spectral parameters is different for the different regions. But for their absolute intensity in the low energy region (0.15–1.0 keV) the X-ray spectra for all the four regions shown in Figure 5 appear to be similar. The data for the Fornax region appear quite well behaved. However, there appears to be a shoulder at 2.5 keV in Telescopium-Tucanae and a knee at about 1.1 keV both in Eridanus and region D.

A general conclusion of the galactic origin of the enhanced regions is immediately obvious from the Figure 5. The observed intensities below 1 keV far exceed the expected flux from the extragalactic component. The descriptive parameters for the spectra of enhanced emission are computed under the assumption of thermal models. The calculations for the thermal emission of optically thin plasma with cosmic abundances (Allen 1973) by Kato (1976) in the temperature range 10^5–10^7 K are used for computing the soft X-ray spectrum.

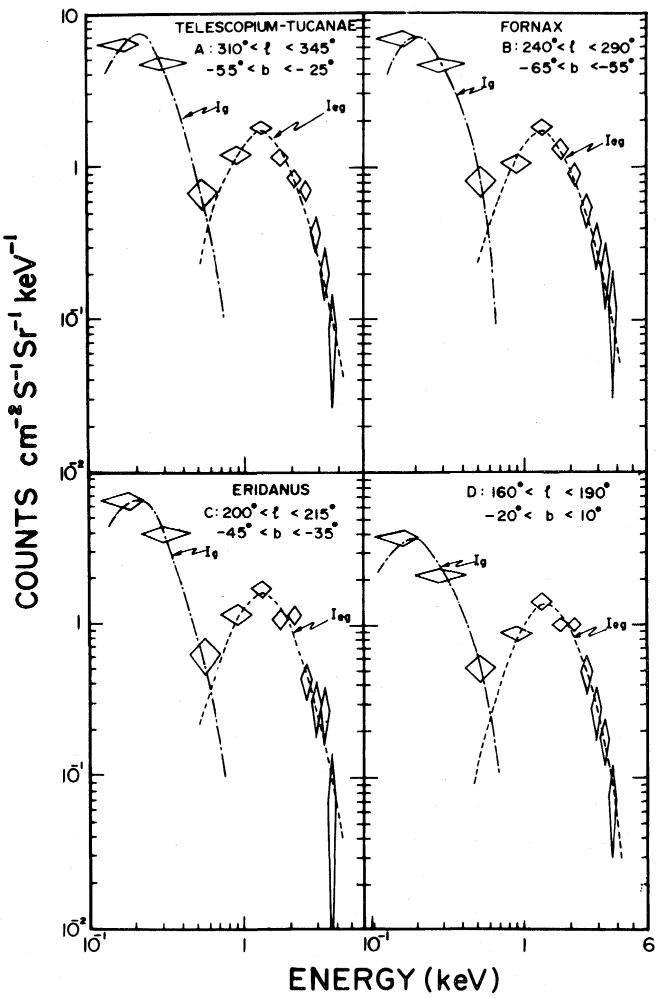

FIGURE 5 The energy spectra observed from four regions. The galactic and extragalactic components are shown separately as I_g and I_{eg} respectively.

In a simple model, it is sufficient to consider the following two cases for the spatial distribution of hot plasma:

(i) A region of hot plasma lies outside an absorbing layer of neutral matter in the galaxy. The X-ray intensity from such a hot plasma cloud at temperature T and average electron density n_e radiating through a cold intervening amount of $\mathrm{N_H}$ of cold gas is given by

$$I_p^g(E) = \frac{\lambda(E,\ T)}{4\pi E}\, n_e^2 R_x \exp(-\sigma(E)\mathrm{N_H}) \tag{1}$$

where $\sigma(E)$ is the photoelectric absorption cross-section for equivalent H atoms of the interstellar matter (Brown and Gould 1970), $\lambda(T,\ E)\ n_e^2$ is the average volume emissivity computed from the Kato plasma code (Kato, 1976) and R_x is the depth of emitting region along the line of sight.

(ii) Regions of hot plasma with uniform electron density n_e could be interspersed with neutral cold gas with average hydrogen density n_H and total column density $\mathrm{N_H}$ in the line of sight. The X-ray intensity from such a composite mixture of hot plasma is given by

$$I_{l\,p}^{g}(E) = \frac{1}{E}\,\frac{\lambda(T,\ E) n_e^2 f_x}{4\pi\sigma(E)\cdot n_\mathrm{H}}\cdot(1\text{-}\exp(-\sigma(E)\cdot \mathrm{N}_{11})) \tag{2}$$

where f_x is the filling factor of regions of hot gas in the interstellar medium.

In the low $\mathrm{N_H}$ limit the expression (2) converges to Eq. (1). Since all the four regions discussed in the present data are in the direction of low $\mathrm{N_H}$ ($\mathrm{N_H} < 3 \times 10^{20}$ H atoms cm^{-2}), we adopt the first case for fitting the spectral data. The flux values in the energy band ΔE, when convolved with the detection efficiency and resolution, are given as

$$F_p(\Delta E) = \frac{1}{4\pi}\Lambda(T,\ \mathrm{N_H},\ \lambda,\ \Delta E) n_e^2 R_x \tag{3}$$

where Λ is the integrated specific volume emissivity in energy band ΔE after the convolution.

The best fit thermal parameters for the low energy data points shown in Figure 5 are $T = 1.6 \times 10^6$ K and $\mathrm{N_H} = 0$, and the range for the predicted parameters is $1 \times 10^6 < T < 2 \times 10^6$ and $\mathrm{N_H} < 3.10^{20}$ H atoms cm^{-2}. Negligible absorption in the line of sight for the soft X-rays, even in the direction of region D which corresponds to near disk density of neutral hydrogen (21 cm data) clearly indicates that the radiating plasma is local in character. Also, the similarity of spectra in the four regions can be interpreted as the enhanced emission originating in similar physical conditions of the hot plasma cloud, the only difference being in the emission measure. The emission measure ($\mathrm{EM} = n_e^2\ R_x$) is $(4.3 \pm 1.7)\ 10^{-3}$ cm^{-6} pc for the regions A, B and C, and $(2.0 \pm 0.4)\ 10^{-3}$ cm^{-6} pc for the region D. The limited statistics of our data do not justify attempts to fit them with models of variable abundances or multitemperatures. A decrease of about 15% in the EM is expected for different models with depleted abundances (Burstein *et al.* 1977).

N_H correlation of the C-band intensity as shown in Figure 4 is completely in contrast with the expected exponential attenuation from Eq. (1). Coupled with the negligible absorption observed in the line of sight ($N_H < 3 \times 10^{20}$ H cm^{-2}), even in the direction of region D which corresponds to near disk density of neutral hydrogen, this suggests that emission regions are local in character. Hence the directional variation of the C-band flux may either be due to a difference in emission measure or produced by selective absorption in C-band in the interspersed plasma.

ERIDANUS "HOT SPOT"

Among the three broad regions of enhanced emission, region C coincides with the Eridanus "hot spot" (Naranan *et at.* 1976). On the basis of positional association with optical filaments (Sivan 1974), an expanding shell of neutral hydrogen (Heiles and Jenkins, 1976), O VI absorption in this direction (York 1974) and similarity of this region with Cygnus loop and Vela-X SNR's Naranan *et al.* suggested that Eridanus hot spot may also be a SNR at a distance of 200 pc having an angular diameter of about 15°. The excess in this region was also visible in the earlier surveys of Williamson *et al.* (1974) and Davidsen *et al.* (1972); more recently Long *et al.* (1977) have suggested that the Eridanus excess may be simply due to N_H minimum in this direction. A later survey of this region was made by Zwijnenberg *et al.* (1976), who found a discrepancy by a factor of about 2 in the flux values compared to Naranan *et al.* A comparison of the present measurements with earlier results is given in Table I. The flux values obtained in the C-band compare very well with Long *et al.* (1977) and are consistent with other authors each of whom has an uncertainty factor ~2 in the flux evaluation.

Because of the striking similarity between the spectra of "Eridanus" and the other two regions in Telescopium-Tucanae and Fornax, shown in Figure 5, there is no compelling need to invoke specific models to explain the excess emission from Eridanus region. Our flux values can be easily interpreted in terms of local galactic emission. Figure 6 shows superposition of the counting rate distribution of our data on the optical and radio features for the low and high energy intervals. The spatial structure observed in the present experiment is in rough agreement with that reported by Naranan *et al.* (1976) and Zwijnenberg (1976); however our observations indicate that the maximum emission in C-band emanates from a narrow region in

TABLE I

Comparison of the reported flux from Eridanus "hot spot" with the present observations

Observer	Energy Band (keV)	Flux (10^{-9} ergs cm^{-2} sec^{-1})
Naranan *et al.* (1976)	0.18–0.28	0.7
	0.8–2.0	2.0
Zwijnenberg (1976)	0.2–1.0	1.2
Long *et al.* (1977)	0.15–0.28	0.4
Present work	0.1–0.28	0.37
	0.7–1.5	1.5

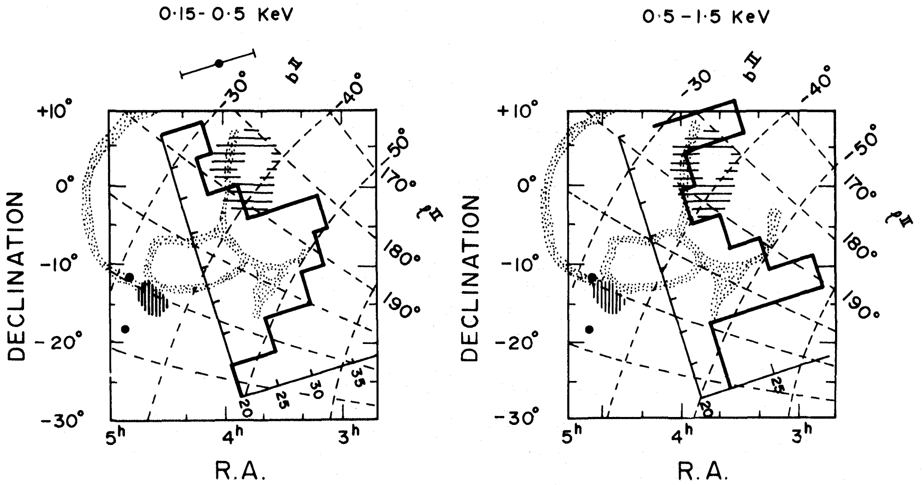

FIGURE 6 C and M-band counts from the Eridanus "hot spot" plotted on the optical and radio features in the same region: optical filaments (dotted region), radio and H II emission (horizontally shaded), region of H I velocity shift (vertically shaded) and two pulsars *viz.*, PSR 0447-12 and MP 0450-18 (two big dots).

the center of the hot spot. The M-band excess seems to be much more extended and even indicative of shell structure supporting a shock front.

DISCUSSION

From the spectral analysis shown in Figure 4, it is quite clear that two components are required to fit the data in all the regions. The extragalactic contribution accounts for all the measured flux values above 0.8 keV and the flux values deduced from our data are in agreement with the earlier observations (Hayakawa *et al.* 1973, Long *et al.* 1977, and Fried 1978). For the low energy data attributed to galactic emission, a single component model is acceptable.

Present data are consistent with the hypothesis that soft X-rays observed from the extended regions of excess emission arise from a local hot cloud interspersed with cold gas. Hot galactic halo or a disk source much larger than the neutral hydrogen disk is not at all compatible with the data. However, it should be remarked that the soft X-ray emission region must be shielded by an absorbing layer with $N_H \sim 3 \times 10^{21}$, which is required to fit the high energy data even in the direction of N_H minimum.

Our conclusions support the local origin as suggested by Hayakawa *et al.* (1978) and Sanders *et al.* (1977) with a probable foreground absorbing gas as shown by Matsuoka (1979). A gradual N_H dependence of soft X-ray intensity (Figure 4) and the fact that the observed value of N_H in these directions resembles the one measured from 21 cm data, suggest that the cold gas is displaced by the hot plasma into a foreground absorbing layer.

The diffuse background in the southern latitudes as obtained in this experiment shows only gradual variation in contrast to the steep latitude dependence as seen in north latitudes and the present results are in agreement with those reported by Iwanami *et al.* (1979) for other regions of the Southern galactic hemisphere.

The thermal nature for the soft X-ray background is consistent with the high temperature phase of the interstellar medium as discovered with O VI absorption line in stellar spectra (Jenkins 1977). The ionization fraction of O VI has a sharp peak at $T \sim 3 \times 10^5$ K, above which it falls sharply. However, Hayakawa *et al.* (1978) have argued that O VI results are consistent with a local plasma region with temperature $T \simeq 10^6$ K and average electron density of $(0.5\text{–}3) \times 10^{-2}$ cm^{-3}. The O VI column density due to hot plasma in the direction of a star is given by:

$$N_{\mathrm{O\,VI}} = (0.4\text{–}1.6) \times 10^{12}\,(CR_x)^{-1/2} R \ \mathrm{cm}^{-2} \ \text{for cosmic abundance}$$

where R_x and R are the linear distances of X-ray source region and the stellar distance in pc and the clumping factor $C = \langle \mathrm{Ne}^2 \rangle / \langle \mathrm{Ne} \rangle^2$. The measured values of $N_{\mathrm{O\,VI}}$ for π Sco and η UMa put a limit on the size of X-ray region (Tanaka, 1977) such that

$$30 \ \mathrm{pc} \leq R_x \leq 100 \ \mathrm{pc}$$

If we take the value of $R_x \sim 100$ pc in the direction of enhanced emission, then for our inferred values of the emission measure of about $(4.3 \pm 1.7) \times 10^{-3}$ cm^{-6} pc, we get $n_e \sim 6.5 \times 10^{-3}$ cm^{-3}. This value of electron density compares with that required for X-ray plasma to be compatible with the O VI measurements. The pressure of the local hot plasma is then given by $p/\mathrm{K} = 2n_eT \simeq 2 \times 10^4$ cm^{-3} K which is an order of magnitude larger than the present estimates of about 2000 cm^{-3} K (Shapiro and Field 1976). Hence the local hot plasma is still not in pressure equilibrium with the surrounding cool matter and therefore is expanding. Also a low electron density of about 6×10^{-3} is attainable in medium swept by a supernova blastwave. This means that hot interstellar plasma may have its origin in a supernova remnant. About 80% filling of the interstellar space with hot cloud is necessary to explain the absolute emission measure (McKee and Ostriker, 1977) and an input energy of about 10^{52} ergs s^{-1} is essential to maintain the sources.

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