THE DIFFUSE SOFT X-RAY SKY

Astrophysics Related to Cosmic Soft X-Rays in the Energy Range 0.1–2.0 keV

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Abstract. The current status of the investigation of the soft X-ray diffuse background in the energy range 0.1–2.0 keV is reviewed. A consistent model, based on the soft X-ray brightness distribution and the energy spectrum over the sky, is derived. The observed diffuse background is predominantly of galactic origin and considered as thermal emission for the most part from a local hot region of temperature \(\sim10^6\) K which includes the solar system. Several pronounced features of enhanced emission are interpreted in terms of hot regions with temperatures up to \(3 \times 10^6\) K, some of which are probably old supernova remnants. The properties of the soft X-ray emitting regions are discussed in relation to the observational results on \(O\,\,v\,\,I\) absorption.

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1. Introduction

Soon after the discovery of cosmic X-rays in 1962, the presence of an intense diffuse component became evident. This component, well established above 2 keV, has now been generally accepted as being of extragalactic origin because of its isotropy (see for instance an excellent review by Schwartz and Gursky (1973)). Mainly due to technical difficulties, the X-ray sky below 2 keV had been left unexplored until the first successful attempt in 1966 (Bowyer et al., 1968).

Subsequent experiments quickly revealed the important facts that the observed intensity below 2 keV is well in excess of the extrapolated isotropic component even without taking into account the galactic absorption and that a finite flux exists in the direction of the galactic plane where no extragalactic component below 2 keV could arrive unabsorbed. Thus, it became apparent that a new soft component dominates the background below 2 keV and a substantial part of it is of galactic origin.

Comprehensive reviews of this soft X-ray diffuse background were published by Silk (1970, 1973), and more recent results were summarized by Seward (1974) and by Bunner (1975).

Observations of discrete sources in the energy range below 2 keV have also been in progress. The most up-to-date review on soft X-ray discrete sources has recently been published by Gorenstein and Tucker (1976). We shall, therefore, refer to this review for the discrete sources, and deal in the present review with the diffuse component of soft X-rays.

Concerning the terminology in this paper, we define soft X-rays as photons in the energy range 0.1–2.0 keV. These boundaries are somewhat arbitrary and technical, 2 keV is practically the lower detection boundary for the most commonly used beryllium-window X-ray counter. Whereas, below 2 keV, the interstellar absorption of the galaxy sets in and at the same time the soft X-ray diffuse component we are dealing with here becomes significant. The energy range below 0.1 keV may be conveniently called the EUV (extreme ultraviolet) region, which is yet to be explored.

Important progress has been made since the time of Silk's review. Brightness distributions of soft X-rays for almost the entire sky have now become available (Davidsen et al., 1972; Williamson et al., 1974; Naranan et al., 1976; Hayakawa et al., 1975a, de Korte et al., 1976; Burstein et al., 1976). These sky maps exhibit a high degree of complexity of the soft X-ray distribution. No straightforward resemblance is evident to any of the gas, stellar and radio distributions. Varieties of large- and small-scale features have become apparent. The appearance of the brightness distribution is clearly energy-dependent, indicating that the energy spectrum varies over the sky.

Information about the energy spectrum of the soft X-ray diffuse component is still meagre, primarily because of the rather narrow pass bands and insufficient energy resolution of the detector. Available results, however, consistently show that the
spectrum is in agreement with thermal emission from a tenuous high-temperature plasma of the order of $10^6$ K. In the temperature range below $10^7$ K, most of the power of the radiation should be contained in emission lines, in contrast to the range above $10^7$ K where the continuum radiation becomes predominant. Evidence for strong line emission is already available in some part of the sky. Consequently, spectroscopy of soft X-rays is challenging for future experiments.

The recent discovery of O VI absorption lines by the Copernicus satellite (York, 1974; Jenkins and Meloy, 1974) has given new light to the investigation of the interstellar medium. This result implies the existence of a hot tenuous plasma component with temperatures in the range $2 \times 10^5$–$10^6$ K in the interstellar space, which could be well connected with the problem of soft X-rays. In this context, a hypothesis was put forward (Williamson et al., 1974; Cox and Smith, 1974) that the soft X-rays are generated predominantly in a hot plasma which causes the O VI absorption and that a considerable fraction of the interstellar space could be filled with such a plasma formed and reheated by supernova explosions. Although this hypothesis needs close examination, such a high temperature component of the interstellar medium should have a significant influence on the dynamical and thermal properties of the Galaxy. We consider that the soft X-ray diffuse background is directly related to the interstellar medium of the highest temperature phase, and the available results seem to urge reconsideration of the well-accepted picture of the two-phase steady state.

We shall discuss these problems in the following sections, however the interpretations may sometimes be subjective and our survey of the literature is probably incomplete.

In Section 2, the absorption and production of soft X-rays are summarized. Observational aspects which are directly related to the analysis of data are covered in Section 3. A brief survey of the development and the present status of the discussions on the galactic and extragalactic component of the diffuse background is given in Section 4 on the basis of the available soft X-ray sky maps. Section 5 deals categorically with the origin of the soft X-ray diffuse background: whether it is of stellar or non-stellar origin, generated by thermal or non-thermal mechanisms. In Section 6, the regions of enhanced soft X-ray emission are described and interpreted. Formation of hot regions in the Galaxy and observational evidence from the O VI absorption are discussed in Section 7. Using the most recent observational material, we shall attempt in Section 8 to derive a consistent model which can account for overall features. Finally, the properties of the soft X-ray emitting regions and the relation with the results from O VI absorption are discussed in Section 9.

2. Absorption and Production of Soft Cosmic X-Rays

In this section we briefly summarize the physical processes which are of particular importance for a relevant description and understanding of the celestial soft X-rays.
2.1. Absorption

Absorption by interstellar matter, either in the form of gas or dust, plays an important role in observations of soft X-ray sources. The transmitted fraction of an X-ray beam with intensity \( I_0 \), passing through a slab of material with a thickness \( x \) is given by:

\[
I = I_0 \exp \left[ -\mu(E)x \right],
\]

where \( \mu(E) \) represents an energy dependent absorption coefficient which comprises the effects of different X-ray interaction processes.

The interactions which can be considered are free-free absorption, photoelectric absorption, scattering on free electrons and Rayleigh scattering, in which only photoelectric absorption is important in the discussion of the soft X-ray diffuse background.

2.1.1. Photoelectric Absorption

The interstellar medium becomes opaque for radiation with wavelengths shorter than 912 Å (13.6 eV), the hydrogen Lyman-edge. The photoelectric absorption for interstellar matter is usually expressed in terms of an effective cross-section \( \sigma(E) \) per hydrogen atom, Equation (1) then becomes:

\[
I = I_0 \exp \left[ -\sigma(E)N_H \right]
\]

where \( N_H \) represents the hydrogen density integrated over the line of sight towards the X-ray emitting object hereafter called the column density of hydrogen. The optical depth \( \sigma(E)N_H \) for photoelectric absorption plays a major role in the assessment of soft X-ray spectra or, alternatively, in attempts to establish a distance (and consequently a luminosity) scale for X-ray sources.

The photo-electric cross-section for \( K \)-shell ionization in the first Born approximation (high-energy-limit) is given by (Heitler, 1954):

\[
\sigma_K = 4\sqrt{2} \alpha^4 Z^5 \sigma_T \left( \frac{m_ec^2}{E} \right)^{7/2}
\]

with \( \alpha = 1/137 \), \( Z \) the atomic number of the target atom, \( \sigma_T \) the Thomson cross-section, \( m_ec^2 \) the electron rest energy and \( E \) the energy of the interacting photon. For photon energies near the absorption edge the Born condition no longer holds and therefore relation (3) constitutes a poor approximation in the soft X-ray regime, it is however useful to roughly indicate the functional dependences.

For a gas with cosmic abundances the effective cross-section per hydrogen atom is expressed by:

\[
\sigma(E) = \sum_i \frac{n_i}{n_H} \sigma_i(E),
\]

where \( n_i/n_H \) represents the relative abundance of element \( i \) with respect to hydrogen.
and $\sigma(E)$ its photoelectric cross-section. Figure 1 shows the photoelectric cross-section of the abundant elements in the interstellar medium, taken from the work of Cruddace et al. (1974). Accurate numerical values of photoelectric cross-sections for various elements are available in the literature (e.g. Henke et al., 1967). Although hydrogen is the principal constituent of the interstellar gas, the strong $Z$-dependence of $\sigma(E)\sim Z^5$ causes the heavier elements to play a dominant role in the absorption of soft X-rays. Several calculations have been carried out to determine $\sigma(E)$ at soft X-ray energies (Felten and Gould, 1966; Bell and Kingston, 1967; Brown and Gould, 1970; Cruddace et al., 1974).

![Photo-electric absorption cross-sections of the abundant elements in the interstellar medium as a function of wavelength (Cruddace et al., 1974).](image)

Figure 2 shows the relative importance of the various elements for soft X-ray absorption based on the work of Brown and Gould. It is clear from this figure that below 0.53 keV (oxygen $K$-edge) the absorption is mainly caused by He and H, whereas beyond this energy oxygen and the heavier elements dominate. Cruddace et al. have extended the calculation of Brown and Gould towards lower energies, in particular to assess the interstellar absorption in the EUV region ($\lambda > 100$ Å).
Fig. 2. Relative importance of different elements in the interstellar medium for the absorption of soft X-rays (Seward, 1975).

Figure 3 displays $\sigma(E)$ as given by Cruddace et al. For practical purposes, the Brown-Gould cross-section can be approximated by

$$\sigma(E) = \begin{cases} 
0.65 \times 10^{-22} E^{-3} \text{ cm}^2 (\text{H-atom})^{-1}, & 0.1 \text{ keV} < E < 0.53 \text{ keV}, \\
2.0 \times 10^{-22} E^{-2.5} \text{ cm}^2 (\text{H-atom})^{-1}, & 0.53 \text{ keV} < E < 5 \text{ keV}.
\end{cases} \quad (4a)$$

The following points are to be considered for the assessment of the interstellar absorption.

1. Ionization state. A certain degree of ionization of the interstellar gas will leave the absorption above 0.53 keV almost unaffected since the $K$-shell electrons of the heavier elements will still be present. Below 0.53 keV, especially towards the EUV region, the absorption can be appreciably reduced if a large fraction of He and H are in ionized form.

2. Molecular hydrogen. It is unclear what fraction of the interstellar hydrogen is in molecular form. The results of the UV absorption measurements distribute in a large range of the molecular fraction of hydrogen from $10^{-6}$ up to 0.5 for various stars observed (Spitzer and Jenkins, 1975). The observation of CO, OH and more complex molecules in dark clouds supports that a major part of hydrogen in these clouds will reside in molecular form. Since the photoelectric absorption cross-section of molecular hydrogen exceeds twice the value for atomic hydrogen, it does alter the value of $\sigma$ at very low energies but has small effect above 0.1 keV.

3. Grains. A fraction of the heavier elements may reside in the form of grains rather than in gaseous form. For example, Morton et al. (1973) found, from the analysis of interstellar absorption lines in UV-star spectra, that the heavier elements, in particular C, N, O, Si, Mg, Fe were depleted as compared to the 'cosmical' (solar)
abundance. This could be explained if a large fraction of these elements exists in the form of grains. Even so, the typical size of these grains is of the order 0.1 micron and therefore they can still be considered as optically thin for soft X-rays even near the oxygen $K$-edge where the absorption effect is largest. A reduction of effective absorption cross-section compared to a purely gaseous medium due to ‘selfblanketing’ of grains as suggested by Fireman (1974) has negligible effect. On the other hand, Greenberg (1974) has estimated that the total mass of C, N, O which can be accreted on grains is too small to account for the observed depletion of these elements in gaseous form. A real depletion of the oxygen abundance would have a significant effect on the soft X-ray absorption at energies above 0.53 keV.
Small-angle scattering of soft X-rays by interstellar grains has been discussed by several authors (Overbeck, 1965; Hayakawa, 1970) which would cause a halo to be produced around a point X-ray source. This does not concern us here.

2.1.2. $N_H$-value

The value of $N_H$ is normally treated as a free parameter in the analysis of soft X-ray spectra and evaluated according to a best fit procedure. The value derived in this way depends, apart from course from $\sigma$, on the assumed model spectrum for the X-ray source. In case of discrete sources, it also includes the self-absorption by circumstellar material around the source. To arrive at a consistent astrophysical picture, correlations are sought between the amount of $N_H$ derived in this way and those derived from other types of observation. Study of such a correlation also provides an important clue to the distribution and the composition of the interstellar matter. Let us examine a few possibilities.

1) Correlation with 21-cm observation. Comparison of the $N_H$-values from 21-cm radio observations with those derived from soft X-ray measurements have not led to a very consistent picture. One frequently employs an average hydrogen density derived from averaging the 21-cm data over the whole line of sight. For objects at low latitudes this means averaging over several kiloparsecs. This can introduce, due to the irregular distribution along the line of sight, a major deviation from the actual local situation.

The 21-cm data refer only to the atomic part of the hydrogen column, the amount of H II and molecular hydrogen remains undetected. H II regions of a temperature $\sim 10^4$ K should be included for the absorption, since most part of He is not fully ionized. For this reason, the amount of $N_H$ derived from the 21-cm observations may be regarded as a lower limit for X-ray absorption. On the other hand, if a large fraction of the hydrogen is heavily clumped depending on the optical thickness of the clouds, the effective absorption for X-rays is reduced. 21-cm measurements of Greisen (1973) showed an evidence for such clouds in several directions near the galactic plane. The recent work of Heiles and Habing (1974, 1975), who provided $N_H$ maps on a scale of half a degree, does not support this heavy clumping. Recent Arecibo results reported by Dickey et al. (1976) show that such a heavy clumping is not common at moderate and high galactic latitudes, so that this effect may not be too serious. In summary correlation with 21-cm data will remain rather inconclusive.

2) Correlation with optical extinction. It has been suggested that for optically identified sources the optical extinction $A_v$ should well correlate with the amount of $N_H$ derived for optically thin X-ray sources (Reina and Tarenghi, 1973; Gorenstein, 1975; Ryter et al., 1975). The argument is that the grains which cause the optical extinction by scattering are condensates of the heavier elements in the interstellar gas which are, above 0.53 keV, directly responsible for the X-ray absorption. Gorenstein and Ryter et al. derived an empirical relation between the amount of $N_H$ derived for several soft extended X-ray sources (optically thin) and the colour excess of their visual counterpart: $N_H/E(B-V) \equiv 7 \times 10^{21}$ H I atoms cm$^{-2}$ mag.$^{-1}$
\( (A_v = 3E(B - V)) \). It would appear that this type of correlation is physically very meaningful for X-ray sources with significant absorption above 0.53 keV.

(3) **Correlation with Lα absorption.** Satellite-borne UV-spectrometers have enabled the measurement of Lα absorption (1216 Å for atomic hydrogen, <1108 Å for molecular hydrogen) in the spectra of several tens stars (Rogerson et al., 1973a; Savage and Jenkins, 1972; Jenkins and Savage, 1974; Bohlin, 1975). These data give the best clue to interstellar conditions in the solar neighbourhood (out to several hundred parsec) and indicate that the local conditions concerning matter density deviate appreciably from the average derived from the 21-cm results.

The neutral hydrogen density derived from the absorption spectra of about ten stars at a distance closer than a hundred parsec indicate values smaller than 0.1 cm\(^{-3}\), much lower than was expected from 21-cm data. Since the brightness distribution for soft X-rays below 0.28 keV is entirely determined by the local interstellar conditions, correlation with Lα absorption measurements contains the smallest ambiguities for the assessment of the local very soft X-ray picture.

### 2.2. Soft X-ray Emission

The X-ray emission processes can be subdivided in thermal and non-thermal processes.

(1) **Thermal X-rays**

A hot low-density plasma emits thermal X-rays by means of thermal Bremsstrahlung (free-free transition) and radiative recombination (free-bound transition), constituting the X-ray continuum, and line emission (bound-bound transition). For thermal X-ray sources with a plasma temperature above 10\(^7\) K, the Bremsstrahlung dominates the emission and determines the spectral shape. For a Maxwellian velocity distribution of electrons, the differential volume emissivity is given by

\[
q_{ff} = 1.0 \times 10^{-11} n_e n_i Z^2 gT^{-3/2} \exp(-E/kT) \text{ eV cm}\(^{-3}\) s\(^{-1}\) eV\(^{-1}\),
\]

where \( n_e, n_i \) are the electron, ion density, \( E \) the photon energy in eV and \( g \) an energy-dependent Gaunt factor. For a pure hydrogen plasma, \( g \) is given in the Born approximation by

\[
g = \pi^{-1/3} \exp\left(E/2kT\right)K_0(E/2kT),
\]

where \( K_0 \) is the modified Bessel function of the zeroth order. An accurate calculation of the Gaunt factor was performed by Karzas and Latter (1961). For temperatures below 10\(^7\) K, Equation (6) deviates significantly from the values of Karzas and Latter. Unless an accurate value is required, an approximate value for the temperature range, 10\(^5\)–10\(^7\) K, and for the range of \( E/kT \), 0.1–10, is obtained from

\[
g \approx 2.0(10E/kT)^{-0.1\log T+0.36}.
\]

The effective Gaunt factor for the cosmic plasma, where heavier ions are included, is only less than 10% different from that for pure hydrogen plasma.
For soft X-ray sources the temperature regime \(10^{5} - 10^{7}\) K is to be considered. In this case, the contribution from radiative recombination, line emission and two-photon decay becomes quite important and has significant influence on the spectral shape. Computation of thin hot plasma spectra including these contributions have been given by several authors (Landini and Fossi, 1970; Tucker and Koren, 1971; Mewe, 1972; Kato, 1976; Raymond et al., 1976) assuming solar coronal abundances. Kato derived the spectrum over the wavelength range 1–250 Å for plasma temperatures \(10^{5} - 10^{7}\) K including 795 emission lines. Figure 4, taken from Kato's paper, shows the line emission power as a function of temperature in several

![Graph showing line emission power as a function of temperature.](image)

Fig. 4. Line emission power in various wavelength bands as a function of temperature. The emission power of Bremsstrahlung (B) and of recombination (R) is also indicated (Kato, 1976).
wavelength bands, for comparison the power radiated in free-free and free-bound transitions is indicated. It is clear from the figure that in the temperature range below $2 \times 10^6$ K the power radiated in lines dominates the continuum emission and is consequently of fundamental importance for the evaluation of soft X-ray spectra.

(2) Non-Thermal X-Rays

Non-thermal mechanisms include synchrotron emission, inverse Compton effect, and non-thermal Bremsstrahlung. For soft X-ray emission all these processes never dominate the efficiency of thermal emission, apart perhaps from very specific conditions (very strong magnetic fields, high fluxes of relativistic particles, extraordinary photon densities, etc.) possibly in compact sources and some extragalactic sources.

The differential volume emissivity for inverse Compton scattering, assuming a power-law differential energy spectrum for the electron flux $J_0 E^\gamma \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \, \text{eV}^{-1}$ and a black body photon field at temperature $T$, can be approximated by

$$q_{ic}(E) = 2.1 \times 10^{-35} (2.9 \times 10^7)^{3-\gamma} J_0 \rho_{bb} T^{(\gamma-3)/2} \times E^{-\gamma/2} \, \text{eV cm}^{-3} \, \text{s}^{-1} \, \text{eV}^{-1}$$

with $\rho_{bb}$ the energy density of the photon field in eV cm$^{-3}$.

For synchrotron radiation,

$$q_s(E) = 6.4 \times 10^{-25} (3.9 \times 10^9)^{3-\gamma} J_0 H^{(\gamma+1)/2} E^{-\gamma/2} \, \text{eV cm}^{-3} \, \text{s}^{-1} \, \text{eV}^{-1}$$

with $H$ the magnetic field strength in gauss.

From (7) and (8) an emissivity ratio follows:

$$\frac{q_s(E)}{q_{ic}(E)} = 1.2 \frac{\rho_m}{\rho_{bb}} \left( \frac{1.8 \times 10^4 \, T}{H} \right)^{(3-\gamma)/2}$$

with $\rho_m/\rho_{bb}$ the ratio of energy densities between the magnetic field and the photon field.

We shall examine the relevance of these mechanisms in comparison with the observational results in Section 5.

3. Observational Aspects

We shall outline here the measurement techniques used in soft X-ray observations so far. We shall not discuss specific technical aspects like proportional counter design, grazing incidence X-ray optics, collimators etc., but rather focus on the general instrument characteristics which are of importance for interpretation of the observational data. This includes a short discussion of several sources of non-X-ray background.
3.1. Instrument Response

The principal detection device for soft X-rays is the proportional counter. Directionality is obtained with the aid of collimators, normally consisting of a honeycomb structure, arrays of metal slats or a stack of metal meshes. The collecting power of this type of instrument is determined by the total effective area of the proportional counter. It has been frequently used in the past, particularly in sounding rocket experiments, for the observation of the diffuse soft X-ray sky with typical angular resolution of several degrees. Grazing incidence optics, which focusses the collected X-rays on a small proportional counter in the focal plane largely improves the signal to noise ratio and has occasionally been used for diffuse background observations (Yentis et al., 1972; Bleeker et al., 1977). However the required focal length is a large constraint on the total collecting area which can be achieved in a typical rocket experiment as compared to the collimated proportional counter. The development of high resolution grazing incidence telescopes has therefore mainly been driven by need for the positioning, imaging and spectroscopy on discrete sources.

Generally the number of counts detected by an X-ray telescope from a diffuse radiation field in a pulse-height interval $\Delta E$ can be expressed by

$$N(\Delta E) = \int_{\Delta E} dE' \int_{\Omega} \int_{0}^{\infty} S(E, \theta, \phi) \exp[-\sigma(E)N_{H}(\theta, \phi)]$$

$$\times P(E, \theta, \phi)F(E, E') dE \ d\Omega,$$

(10)

where $S(E, \theta, \phi)$ represents the source function, $\sigma(E)N_{H}$ the optical depth of the intervening gas, $\Omega$ the angular extent of the source, $P$ the effective collecting power of the telescope and $F(E, E')$ the spectral response (energy resolution) function of the detector. The collecting power $P$ can be derived from:

$$P(E, \theta, \phi) = R(E, \theta, \phi)\eta(E, \theta, \phi)G(\theta, \phi)$$

(10a)

in which $R$ is the reflection efficiency of the X-ray optics, $\eta$ the efficiency of the detector and $G$ the geometrical collecting area of the telescope. $R$ is given in the literature for several reflection coatings (Lukirskii et al., 1964; Ershov et al., 1967). Most experiments on diffuse X-rays did not use X-ray reflectors, in which case $R = 1$. Care should be taken of the reflection of soft X-rays at the collimator's (honeycomb or slats) inner surface, which gives an excessive contribution in particular at longer wavelengths ($R > 1$). The detector efficiency $\eta$ can be written as

$$\eta(E, \theta, \phi) = (1 - \exp[-\mu_{G}(E)x_{G}(\theta, \phi)])\exp\left[-\sum_{i}\mu_{i}(E)x_{i}(\theta, \phi)\right]$$

(10b)

with $\mu x$ the optical depth.

The first factor represents the absorption by the counter gas the second factor accounts for the net transmission of beam filters (if incorporated), coatings and detector entrance window. It may, also, include the effect of a residual atmosphere. For energies lower than 1 keV the absorption term is unity in all practical cases. To
obtain a significant transmission for soft X-rays it is necessary to use very thin low-Z material (absorption $\sim Z^5$) for the detector window. Thin organic films with typical thickness of 1 micron and good mechanical properties have been developed for this purpose like biaxially stretched polypropylene (Hayakawa et al., 1970), Formvar (Henke, 1965; Spivack, 1970; Williamson and Maxon, 1975), Parylene N (Spivack, 1970) and Kimfol (Bunner et al., 1969).

Figure 5 shows the transmission functions for commonly used films of different thicknesses, 0.5 micron polypropylene being the thinnest film layer used so far in flight instruments on rockets. For comparison, the attenuation by the interstellar matter for $N_H = 10^{20}$ hydrogen atoms cm$^{-2}$ is also shown. Figure 6 shows the typical influence of an instrument response function on a thermal Bremsstrahlung source at $5 \times 10^6$ K, for 1 $\mu$m and 3 $\mu$m thick polypropylene windows. The effect of the detector spectral resolution is also shown.

![Graph](image_url)

Fig. 5. Transmission probability vs X-ray energy for various plastic films. The attenuation by interstellar matter with a hydrogen column density $N_H = 10^{20}$ atoms cm$^{-2}$ is shown for comparison.

It is clear from Figure 6 that (1) the incident spectrum is considerably deformed by the window transmission of the counters and that (2) the energy resolution of a proportional counter (typically 80% FWHM at 0.28 keV) is too poor to permit a meaningful deconvolution procedure in particular below the $K$-absorption edge of carbon (0.284 keV). Usual approach is the other way round. The best fit to a set of observational data is normally obtained by assuming a model source spectrum, e.g. thermal radiation from a hot plasma, and a certain amount of interstellar absorption. From relation (10) a series of expected values $N(\Delta E)$ are computed (pulse-height histogram) which are then compared with the measured values $M(\Delta E)$ using
chi-square analysis. Variation of a characteristic source spectrum parameter (e.g. kT or $\gamma$) and the value of $N_H$ yields a best fit in dual parameter space. Statistical problems on the qualification of models and parameter estimations are discussed by Lampton et al. (1976).

A consequence is that the amount of $N_H$ derived depends on the assumed shape of the source spectrum as was already mentioned under 2.1. If the source spectrum can be separately established, for instance for discrete sources which radiate also in the 2–20 keV band where the interstellar absorption plays no role, the absorption measure can be directly obtained. To obtain the $N_H$ value in practice with acceptable accuracy, the efficiency of the instrument $R(E)\eta(E)$ should not be much less than $1/e$ at the energy where $\sigma N_H$ becomes unity. In practice this boils down to the requirement $\tau_w \leq \sigma N_H$ at the extinction energy ($\tau_w$ optical depth of the detector window). If $\tau_w \gg \sigma N_H$, the absorption in the detector window dominates, and obviously no accurate determination of $N_H$ can be made. Systematic errors due to window non-uniformities also become large.

The above described approach may be called a ‘direct’ spectral analysis. On the other hand, by utilizing two or more well-separated energy pass bands, one can
qualitatively assess the spectrum and unambiguously evaluate differences in the spectral shape between emission regions. This 'relative' spectral analysis or 'multicolor' method can be successfully applied even when the transmission band width is much narrower than the energy resolution of the counter. For this purpose, transmission bands which open below the K-edges of carbon (0.28 keV), boron (0.18 keV), fluorine (0.67 keV), etc., are useful. The Wisconsin group has been very successfully utilizing the carbon-band and the boron-band (Williamson et al., 1974; Burstein et al., 1976).

Furthermore, the requirement that the model spectra should consistently fit the measurements obtained with instruments with well-known differences in response function reduces the freedom of the models and the parameters, and also eliminates several sources of systematic errors which can occur in an instrument with a single response function. For example, the difference in transmission characteristics gives a very sensitive consistency check when spectra are simultaneously measured by detectors with different filters and/or entrance windows. This method has been successfully used by the Leiden/Nagoya groups employing polypropylene film of various thicknesses (Bleecker et al., 1972; Hayakawa et al., 1975a, de Korte et al., 1976).

3.2. Non-X-ray background

The intensity and spectrum of a discrete source can be derived from the observational data in a relatively straightforward fashion. On the other hand, the evaluation of the non-X-ray background level is of essential importance for the analysis of the diffuse component, since obvious brightness contrasts are rare. Three different sources of non-X-ray background can be identified: (1) the cosmic-ray induced or inherent detector background, (2) low-energy background induced by far UV-photons and (3) low energy electrons. Their magnitude, particular problems and remedies are briefly described.

(1) The Cosmic-Ray-Induced Background

This background component arises from interaction of energetic radiation (minimum ionizing particles, gamma-rays) with the detector material. Anti-coincidence and rise-time discrimination techniques can be used to reject this background, though the latter technique becomes inefficient below 1 keV. The residual flux can be measured during the observation by screening the detector from incoming X-rays, for instance before the nose cone ejection or by using a 'shutter' which can close the field of view (Hayakawa et al., 1971a; Bleeker et al., 1972). It has been shown that using the Earth as an occulting body also gives a representative measurement (Deerenberg, 1973). The energy spectrum arising from this background component is nearly flat. In most of the diffuse background observations the correction is rather small, approximately 10% near 2 keV, negligible in the L-band (<0.28 keV). The use of imaging X-ray optics in the near future combined with small position-sensitive counters in the focal plane will further improve the signal to
noise ratio and will essentially make diffuse background observations photon-limited as far as this background component is concerned.

(2) **UV-Induced Background**

Plastic windows like polypropylene transmit UV-radiation down to 1600 Å (Hayakawa et al., 1970). The quantum energy of UV-photons with wavelengths shortward of 2500 Å exceeds the photoelectric work function of the conductive coating (usually colloidal carbon) used on the plastic entrance window and, possibly, of the counter walls. Consequently single electrons are released in the counter gas giving rise to a pulse height distribution whose tail can contaminate the low-energy part of the ‘true X-ray’ spectrum, depending on the UV-brightness of the sky region observed. Since the single-electron spectrum is very steep, the influence of UV-photons is usually confined below 0.2 keV. Several experiments have suffered from this source of background (Palmieri et al., 1971; Deerenberg, 1973; Hayakawa et al., 1975). The UV-sensitivity was established from the detection of bright B1-stars like α Vir and β Cen. An iterative method to correct for UV-contamination in diffuse X-ray spectra, employing the difference in transmission for UV-radiation and X-rays between windows of different thickness, has been described by de Korte (1975).

Much effort has recently been put in reducing the UV-sensitivity of soft X-ray counters. Williamson and Maxon (1975) have added Lexan, which is an excellent absorber for UV-radiation below 2400 Å, to Formvar for window fabrication. This essentially resulted in a cut-off in UV-transmission of the counter-windows below 2400 Å, leaving the UV-sensitivity negligible. A similar procedure was used by the Leiden/Nagoya groups for a recent rocket experiment, in which thin polypropylene windows were covered with a Lexan-Formvar coating. An inflight check on α Vir proved that the instrument was completely insensitive to UV-radiation down to the low energy threshold of 60 eV (Bleeker et al., 1977).

(3) **Low-Energy Electrons**

The presence of suprathermal electrons at rocket and satellite altitudes has caused severe problems in the observation and interpretation of soft X-ray background data (Hill et al., 1970; Heikkila, 1971; Hayakawa et al., 1973, 1974; Kohno, 1973; Seward et al., 1974). The electron flux largely varies in correlation with the level of geomagnetic activities, but a finite flux is found to exist even at the time of the lowest geomagnetic activity.

The spatial distribution of these electrons is interpreted as comprising two components (i) a component which is almost isotropic in the upper hemisphere with respect to the geomagnetic line of force, representing precipitating electrons along the line of force and (ii) a quasi-trapped component gyrating predominantly in a plane perpendicular to the magnetic line of force (Kohno, 1973; Seward et al., 1974). Above 150 km, the precipitating component appears little dependent on altitude, whereas the quasi-trapped component increases sharply with altitude. The relative intensity and pitch-angle distribution observed as a function of the altitude are shown
in Figure 7 (Nagase, 1974, private communication). The pitch-angle distribution with respect to the local geomagnetic line of force seems fairly reproducible.

Preventing these electrons from entering the detector has been implemented most successfully by means of magnetic deflection in the collimator (Seward et al., 1974). Otherwise, in proportional counters with two detection layers in mutual anticoincidence, the bottom section provides uncontaminated X-ray data in the energy range where the top section becomes transparent. Comparison of the spectra registered in the top and the bottom sections yields an estimate of the residual electron flux (e.g. McCammon et al., 1971). The use of grazing-incidence optics with adequate baffling of any direct ray paths to the focal plane will undoubtedly be an efficient protection against electrons.

Several methods can be used to at least estimate the possible level of electron contamination in the observational data. The electron component shows a significant increase with altitude above 150 km, in contrast to a soft celestial X-ray flux for which the residual atmospheric absorption becomes negligible in this altitude range.

If detectors with entrance windows of different thicknesses are employed, one can use the property that the ratio between X-ray and electron transmission depends on

Fig. 7. The relative intensity and pitch angle distribution of suprathermal electrons as a function of altitude, measured at a geomagnetic latitude of 20° N, presented in a polar diagram with respect to the direction of the local geomagnetic line of force B (Nagase, 1974).
the window thickness. The Earth occultation of soft X-rays can also be useful for the estimation of the electron background.

Validity of the correction applied for the electrons can be examined to a first approximation by comparing the observed spectrum above 2 keV corrected also for the cosmic-ray-induced background with the spectrum expected from the isotropic diffuse component which can be well approximated by $11E^{-1.4}\text{ cm}^{-2}\text{ s}^{-1}\text{ sr}^{-1}\text{ keV}^{-1}$.

4. The Soft X-Ray Sky

It is convenient to subdivide the energy range at the $K$-absorption edge of carbon (0.284 keV), since the observed data we discuss here are all obtained with proportional counters having plastic windows. Throughout this review, we shall designate the passband below 0.28 keV L (low energy)-band. The effective width of the L-band depends upon film thickness and the kind of plastic (see Figure 5). The passband above 0.28 keV will be called M (medium energy)-band. The upper bound of the M-band is chosen as convenient at 0.8 keV or 1.0 keV, above which one sometimes employs the H (high energy)-band. The range for each passband will be specified if necessary.

The measured pulse height will also be expressed in keV. Even for the poor energy resolution of proportional counters, the L-band and M-band can be separated at about 0.4 keV pulse height with a relatively small amount of 'spill-over' from each other, owing to the deep absorption trough in the window transmission characteristics immediately above the carbon $K$-edge.

4.1. First results

The first observations of the diffuse sky background in the L-band were made by Bowyer et al. (1968) and Henry et al. (1968). The intensities recorded, although not in mutual agreement, were appreciably higher than what was expected from an extrapolation to lower energies of the isotropic X-ray background above 2 keV. Subsequent observations (Bunner et al., 1969; Hayakawa et al., 1971a, 1972; Davidsen et al., 1972) confirmed the existence of an 'excess' flux of diffuse soft X-ray emission. Even from the first crude picture which emerged, the following characteristics were evident:

(i) In the L-band the north galactic pole region was much brighter than expected from an extrapolation of the power law spectrum established above 2 keV, even when no interstellar absorption is taken into account.

(ii) The galactic plane flux, though less intense than the north pole, remained finite. This is an unequivocal clue for the existence of galactic emission, since extragalactic soft X-rays incident in this direction should be fully absorbed.

(iii) The intensity distribution over the celestial sphere was patchy. However, a gross tendency of intensity increase with increasing galactic latitude was observable, indicative of anti-correlation with interstellar matter, although this tendency was noted so far only in the north galactic hemisphere.
As the above-mentioned features became apparent, two alternative interpretations were put forward.

(a) Single Component Model

One interpretation was to attribute the soft X-ray emission to a region which belongs to our own galaxy. In order to account for the increased brightness in the L-band near the north pole, the scale height of the X-ray emitting region $Z_X$ should significantly exceed the scale height of the gas disc.

Gorenstein and Tucker (1972) suggested that a single component would account for the observed latitude dependence in the northern hemisphere, if a source distribution with a scale height $Z_X = 800 \text{pc}$ is assumed.

On the other hand, Davidsen et al. pointed out that such a model provides an acceptable fit only in the L-band, but that the latitude dependence at higher energies (near 0.7 keV) expected from such a ‘disc-shaped’ distribution contradicts the observation.

(b) Two-Component Model

As an alternative, Davidsen et al. (1972) suggested a two-component model in which an extragalactic and a galactic component are superimposed. The extragalactic component comprises then the contribution from the power-law spectrum seen above 2 keV and an additional soft component. This model was also extensively discussed by Kato (1972) and Hayakawa et al. (1975a).

Suppose the galactic component originates inside the gas disc with a volume emissivity $q$, uniformly distributed among neutral absorbing gas of mean hydrogen density $\langle n_{\text{H}} \rangle$. Then the expected intensity $I$ is expressed by

\[ I = I_{\text{ex}} \exp(-\sigma n_{\text{H}}) + I_g[1 - \exp(-\sigma n_{\text{H}})], \tag{11} \]

and

\[ I_g = \frac{q}{4\pi\sigma \langle n_{\text{H}} \rangle}, \]

where $I_{\text{ex}}$ denotes the extragalactic component and the second term represents the contribution of the galactic component for a column density of neutral hydrogen $N_{\text{H}}$. Rewriting Equation (11),

\[ I = I_g + (I_{\text{ex}} - I_g) \exp(-\sigma n_{\text{H}}), \tag{11a} \]

in which the second term anti-correlates with $N_{\text{H}}$. This relation appeared to give a qualitative agreement with early observational data in the north galactic hemisphere, although much larger variance was noticed than that expected from pure statistical fluctuation.

An important implication of the two-component model was the hypothesis of the existence of intrinsically soft extragalactic X-rays which originate either from a large-scale galactic halo or from intergalactic space. The latter case invoked a hot intergalactic gas with a density sufficient to close the Universe.
As more observational data became available, however, it presently turned out that the overall brightness distribution of the soft X-ray background was far too complicated, as shown later in Figure 10, to be interpreted in terms of any simple geometrical model like the ones discussed above. Later developments are shown in what follows.

4.2. The Small Magellanic Cloud Experiment

In an attempt to establish the true extragalactic fraction of the X-ray background in the L-band, McCammon et al. (1971) looked for absorption of this component by the gas of the Small Magellanic Cloud which belongs to our Local Group at a distance of 63 kpc from the Milky Way.

Figure 8 shows their observational data. Various absorption models are shown taking into account attenuation by the gas of the SMC+the Galaxy (A), only the SMC (B), only the Galaxy (C) and no absorption except for the extragalactic hard background (D). Apparently the data do not fit any of the absorption models A through C, also not when a certain degree of clumping is assumed (dashed lines). McCammon et al. conclude therefore that no more than 25% of the soft X-ray flux near $\frac{1}{4}$ keV can originate beyond the SMC if the absorption cross-section given by Brown and Gould applies and if the 21-cm observation on the columnar hydrogen in the vicinity of the SMC is reliable. In view of the ambiguity in this last factor, McCammon et al. (1976) have recently reanalyzed the X-ray data using much improved data on the neutral hydrogen distribution. Their new high resolution 21-cm data (0.8) show no small scale structure indicative of significant clumping which could seriously affect the soft X-ray absorption, and the upper limit on the extragalactic component remains unchanged. It could be argued that the SMC emits soft X-rays which would compensate for the absorption, however the lack of absorption by low-velocity galactic gas off the SMC was considered evidence that the bulk of the emission is ‘local’ in origin. The data of McCammon et al. do in fact require no extragalactic component at all in the L-band.

What is the implication of such an upper limit on the existence of intergalactic matter with the critical density? The restrictions imposed from the observational side are summarized in Figure 9 taken from Bunner (1975), $\Omega$ represents the gas density relative to the critical density, $C$ the clumping factor ($\geq 1$) and $z_{\text{max}}$ the largest redshift incorporated in the integration. A lower limit to the allowed temperature range is imposed by the lack of $\La$ absorption in quasars and ranges somewhere between $10^4$ and $10^5$ K depending on the dominant type of ionization. The hard X-ray background observed restricts the high temperature side depending on the value of $z_{\text{max}}$. The upper limit from the SMC experiment gives the largest constraint near $10^6$ K, however it does not exclude the presence of a uniformly distributed gas ($C = 1$) of critical density at $10^6$ K if $z_{\text{max}} = 1$ is assumed.

The limit set for the extragalactic component by McCammon et al. has been confirmed and further squeezed down by later attempts utilizing M31 and the Large Magellanic Cloud (LMC) (Margon et al., 1974; Rappaport et al., 1975; Long et al.,}
Fig. 8. Count rates in the 1-band measured by McCammon et al. (1971) during scans near and over the Small Magellanic Cloud. The solid lines indicate the expected intensity profiles for different absorption models (see text), the dashed lines show the influence of clumping on the absorption models.
Fig. 9. Observational limits on the temperature and density of an intergalactic plasma for a Friedman big bang universe, taken from Bunner (1975).

1976). The most stringent upper limit is set by Long et al. at 9% of the observed L-band flux to originate beyond the LMC. The current status can be seen in Table I. Furthermore, Long et al. stated that 4% of the L-band flux would be accounted for in terms of the power-law part of the extragalactic component only.

These authors also derived upper limits for the galactic 'halo' component as given in the table. It is to be noted, however, that the limit for the halo component was determined from the correlation with varying $N_H$ of our Galaxy in a small area of the sky under the assumption that the intensity of the galactic component therein is constant. This assumption is not a priori justified. In Equation (12), the correlation

<table>
<thead>
<tr>
<th>Experimenter</th>
<th>Object</th>
<th>Local flux (%)</th>
<th>Halo flux (%)</th>
<th>Extragalactic flux (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>McCammon et al. (1976)</td>
<td>SMC</td>
<td>&gt;78</td>
<td>&lt;22</td>
<td>&lt;15</td>
</tr>
<tr>
<td>Margon et al. (1974)</td>
<td>M31</td>
<td>&gt;48 ± 5</td>
<td>&lt;52 ± 5</td>
<td>&lt;52 ± 5</td>
</tr>
<tr>
<td>Rappaport et al. (1975)</td>
<td>LMC</td>
<td>&gt;35</td>
<td>&lt;65</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Long et al. (1976)</td>
<td>LMC</td>
<td>90–94</td>
<td>&lt;9</td>
<td>&lt;9</td>
</tr>
</tbody>
</table>
with \( N_H \) will vanish in the exceptional case \( I_{ex} = I_g \), where the increment of the extragalactic flux with decreasing \( N_H \) is compensated by a decrement of the galactic flux. This possibility seems to be remote from the considerations below, although the halo component, if any, is still an important subject for further investigation.

4.3. Soft X-ray Sky Map and Correlation of Brightness with \( N_H \)

Further observations of the brightness distribution of the soft X-ray diffuse background have thus far covered almost the entire sky (Davidson et al., 1972; Hayakawa et al., 1975a; Williamson et al., 1974; Naranan et al., 1976; de Korte et al., 1976; Burstein et al., 1976). Some of the sky maps are presented in Figure 10.

Apart from the gross tendency discussed above, the examination of the sky maps in Figure 10 indicates several pronounced brightness features, some of which are presumably associated with known galactic features like non-thermal radio loops, \( \text{H}_\alpha \) filaments and neutral hydrogen features. The observed brightness pattern also depends significantly on energy, indicating that the energy spectrum varies over the sky. The particular features and the enhancements will be discussed in Section 6.

From comparison of the soft X-ray brightness with the column density of neutral hydrogen at various position of the sky, one notices two significant points:

(1) The south galactic hemisphere does not exhibit the gross tendency of intensity increase with increasing latitude such as observed in the northern hemisphere. In fact, the south galactic pole is no brighter than some regions near the galactic plane and certainly much less bright than the north pole in the L-band, although the amount of columnar hydrogen is about the same. The absence of an apparent intensity symmetry between the northern and southern hemisphere, which would be characteristic of a large-scale extradisc component such as the galactic halo component, also favors a local origin of the bulk of the soft X-ray diffuse background.

(2) Apart from the above-mentioned north-south asymmetry, the presence of a gross correlation in both the northern and southern hemispheres that soft X-ray brightness increases when \( N_H \) decreases undoubtedy exists. Furthermore, several distinct regions of soft X-ray enhancement do coincide with local \( N_H \) minima. However, the quantitative correlation between the soft X-ray intensity and the amount of \( N_H \) such as expected from Equation (11a) does not hold. Regions of the same \( N_H \) can differ markedly in soft X-ray brightness.

It seems, based on the above arguments, justified to conclude that the soft X-ray background is mainly galactic in origin. The apparent correlation of the soft X-ray intensity with \( N_H \) would have to do with the distribution of the soft X-ray sources within the Galaxy. The gross correlation mentioned above will be more closely examined in Section 8.3.

5. Consideration on the Origin of the Soft X-Ray Diffuse Component

First of all we shall consider if the galactic diffuse component is of stellar origin or composed of truly diffuse emission.
Fig. 10. Soft X-ray maps for several regions on the celestial sphere. All maps are in galactic coordinates. (a) L-band map of the anti-centre region, beam width 10° FWHM (Davisen et al., 1972). (b) L-band and M-band map of the galactic centre region, beamwidth 3° × 18° FWHM. The ridges of the non-thermal radio loops are also indicated (de Korte et al., 1976). (c) L-band map of a part of the southern galactic hemisphere, beam width 10° FWHM. Locations of a few hard X-ray sources are also given (Naranan et al., 1974). (d) L-band map from two Wisconsin rocket experiments, beam width 6° FWHM. (e) M-band map of a portion of the southern galactic hemisphere, beam width 6° FWHM. The black spot is the Crab Nebula (Williamson et al., 1974). (f), (g) L-band and M-band map of the galactic centre region, beam width 6° (Burstein et al., 1976). (h) Preliminary L-band map of the complete southern galactic hemisphere compiled by the Wisconsin group (preliminary unpublished work).
5.1. Stellar origin

Most of the soft X-ray observations were performed with telescopes of moderate angular resolution so that weak discrete sources can not easily be resolved. However, as shown below, the stellar origin hypothesis that the soft X-ray diffuse component is the superposition of soft X-rays from numerous individual stars seems to be excluded.

If the number density of soft X-ray emitting stars is \( n_\star \) and the intrinsic soft X-ray luminosity is \( q_\star \), the soft X-ray intensity \( I \) per unit solid angle is expressed by

\[
I \equiv \frac{n_\star q_\star}{4 \pi \sigma \langle n_{HI} \rangle} (1 - e^{-\sigma N_{HI}}),
\]

where \( \sigma, \langle n_{HI} \rangle \) and \( N_{HI} \) are, respectively, the cross-section for interstellar absorption, the average space density of neutral hydrogen atoms and their column density. Assuming the Brown-Gould cross-section for \( \sigma \) and 0.3 hydrogen atoms cm\(^{-3}\) for \( \langle n_{HI} \rangle \), one obtains \( n_\star q_\star \approx 2 \times 10^{28} \text{ erg s}^{-1} \text{ pc}^{-3} \) for the energy range 0.1–0.28 keV. A star density of \( 7 \times 10^{-2} \) stars pc\(^{-3}\) (Allen, 1973) in the solar neighbourhood gives \( \langle q_\star \rangle \approx 3 \times 10^{29} \text{ erg s}^{-1} \) for the required soft X-ray luminosity averaged over all stars of different types. Incidentally, this value is three orders of magnitude greater than the soft X-ray luminosity of the quiet sun.

Vanderhill et al. (1975) performed a sensitive soft X-ray sky survey and determined 3\( \sigma \) upper limits to the soft X-ray luminosity of 50 nearby stars in about 10% of the entire sky. None of the stars was positively detected to be a soft X-ray source. All of the six observed stars and binaries within 2 pc from the Sun gave 3\( \sigma \) upper limits well below \( 10^{29} \text{ erg s}^{-1} \). From the derived upper limits they conclude that emission from stars is unlikely to account for the soft X-ray diffuse component.

Mewe et al. (1975) also searched for soft X-rays from many nearby stars with a soft X-ray detector aboard the Astronomical Netherlands Satellite (ANS). Except for Sirius and Capella whose soft X-ray emissions were positively detected, none of the observed nine stars within about 10 pc exceeded \( 5 \times 10^{28} \text{ erg s}^{-1} \) at a 3\( \sigma \) upper limit.

With the reasonable assumption that these stars within 10 pc are an unbiased sample of all stars, we may conclude that soft X-rays from stars do not contribute significantly to the soft X-ray diffuse background.

An entirely different approach to the test of the stellar origin hypothesis is the measurement of the small scale fluctuation of the diffuse component. Gold and Pacini (1968) showed that the relative fluctuation \( \delta I/I \) of the soft X-ray intensity through a field of view with a fixed solid angle is related to the number of sources in the field of view \( N \) by \( N = 3^{-3/2}(\delta I/I)^{-3} \). Gorenstein and Tucker (1972) derived the source density \( n_\star \) from the observed \( \delta I/I = 14\% \) with a solid angle of \( 6 \times 10^{-3} \text{ sr} \),

\[
10^{-2} \text{ pc}^{-3} \leq n_\star \leq 1 \text{ pc}^{-3} \quad \text{for} \quad \langle n_{HI} \rangle = 0.8 \text{ cm}^{-3}.
\]

A similar attempt was made by Levine et al. (1976b) who obtained from the observed
\[ \frac{\delta I}{I} = 9\% \text{ per 0.01 sr for a mean energy of 130 eV} \]

\[ n_\star \geq 0.3 \text{ pc}^{-3} \quad \text{with} \quad \langle n_H \rangle = 0.1 \text{ cm}^{-3}. \]

The required number density of sources exceeds the star density of all known types. The large lower limit derived by the latter authors is the result of the smaller average energy of soft X-rays and hence a smaller volume of space to be seen.

Apart from several supernova remnants, soft X-ray sources whose emission predominates below 1 keV are relatively few as compared to the range above 1 keV. These discrete sources have been discussed extensively by Gorenstein and Tucker (1976). We shall therefore refer this matter to their review. Discrete soft X-ray sources so far detected are listed in Table II. It is obvious from the table that very few sources exceed the required luminosity of \( 3 \times 10^{29} \text{ erg s}^{-1} \) in the 0.1–0.28 keV range to account for the intensity of the diffuse component. There are several unidentified soft X-ray sources which were once detected by rocket observations but have not been visible in later observations. These apparently transient sources are also included in the table. Hayakawa et al. (1975c) discussed several examples. In any event, transient sources can hardly account for a significant part of the soft X-ray diffuse background.

5.2. Diffuse emission

From the discussion in the preceding section, it seems most likely that the soft X-ray diffuse component is of a truly diffuse nature. Mechanisms of diffuse soft X-ray emission as mentioned in Section 2 have been discussed by several authors (e.g., Hayakawa, 1973; Williamson et al., 1974). We shall briefly survey these mechanisms here.

(a) Synchrotron Emission

High energy cosmic-ray electrons above \( 10^{13} \text{ eV} \) can emit soft X-rays above 0.1 keV in the galactic magnetic field of a few microgauss. The energy spectrum of electrons can be approximated by \( 2.5 \times 10^{12} E^{-2.6} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ eV}^{-1} \) between \( 10^{10} \) and \( 10^{11} \) eV. If the same power law spectrum is assumed to hold above \( 10^{13} \text{ eV} \) and for 3 microgauss, the estimated soft X-ray intensity from Equation (8) falls short by two orders of magnitude. Furthermore, the electron spectrum is expected to become steeper due to an increasing energy loss rate at higher energies, which results in still larger discrepancy.

(b) Inverse Compton Effect

Electrons above 150 MeV can produce soft X-rays above 0.1 keV by the inverse Compton process with photons of the 2.7 K background radiation with an energy density of 0.25 eV cm\(^{-3}\). Likewise, the process on starlight photons needs electron energies of only 3 MeV and above. Utilizing Equation (7), one finds that this process requires \( 10^4 \) times larger electron flux than that assumed in (a). Furthermore, these
### TABLE II
Soft X-ray sources

(A) Supernova remnants

<table>
<thead>
<tr>
<th></th>
<th>Distance (kpc)</th>
<th>Diameter (pc)</th>
<th>Flux (erg cm(^{-2}) s(^{-1}))</th>
<th>Luminosity (erg s(^{-1}))</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyg loop</td>
<td>0.77</td>
<td>38</td>
<td>0.21</td>
<td>(3 \times 10^{-8})</td>
<td>2 \times 10^{36}</td>
</tr>
<tr>
<td>Vela X</td>
<td>0.5</td>
<td>40</td>
<td>0.22</td>
<td>(1.3 \times 10^{-8})</td>
<td>4.6 \times 10^{35}</td>
</tr>
<tr>
<td>Puppis SNR</td>
<td>2.2</td>
<td>17</td>
<td>0.27–0.30</td>
<td>(4.1 \times 10^{-9})</td>
<td>2.5 \times 10^{36}</td>
</tr>
</tbody>
</table>

(B) Stars

<table>
<thead>
<tr>
<th></th>
<th>Distance (pc)</th>
<th>Type</th>
<th>Temp. (K)</th>
<th>Flux (erg cm(^{-2}) s(^{-1}))(keV)</th>
<th>Energy range (keV)</th>
<th>Luminosity (erg s(^{-1}))</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sirius</td>
<td>2.7</td>
<td>AIV</td>
<td>(10^{-11})</td>
<td>[0.2–0.28]</td>
<td>(10^{28})</td>
<td>[1]</td>
<td></td>
</tr>
<tr>
<td>Capella</td>
<td>14</td>
<td>G8+F</td>
<td>(10^{-11})</td>
<td>[0.2–0.28]</td>
<td>(3 \times 10^{29})</td>
<td>[1]</td>
<td></td>
</tr>
<tr>
<td>HZ43</td>
<td>65</td>
<td>DA</td>
<td>(8 \times 10^{4}) 3 \times 10^{-10}</td>
<td>[0.1–0.28]</td>
<td>(1.4 \times 10^{32})</td>
<td>[1, 2]</td>
<td></td>
</tr>
<tr>
<td>Feige 24</td>
<td>100</td>
<td>DA</td>
<td>(6 \times 10^{4}) 3 \times 10^{-9}</td>
<td>[0.02–0.07]</td>
<td>[3]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS Cyg</td>
<td>100</td>
<td>UG</td>
<td>at flare 5 \times 10^{-10}</td>
<td>[0.15–0.28]</td>
<td>(1.5 \times 10^{33})</td>
<td>[1]</td>
<td></td>
</tr>
<tr>
<td>AM Her</td>
<td>5</td>
<td>UG</td>
<td>at flare 6.5 \times 10^{-11}</td>
<td>[0.15–0.28]</td>
<td>[4]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UV Cet</td>
<td>2.7</td>
<td>dMe</td>
<td>at flare 7 \times 10^{-11}</td>
<td>[0.2–0.28]</td>
<td>(6 \times 10^{28})</td>
<td>[1]</td>
<td></td>
</tr>
<tr>
<td>Prox Cen</td>
<td>1.3</td>
<td>dMe</td>
<td>at flare 8 \times 10^{-10}</td>
<td>[0.07–0.28]</td>
<td>(1.5 \times 10^{29})</td>
<td>[5]</td>
<td></td>
</tr>
</tbody>
</table>

(C) Some published transient sources

<table>
<thead>
<tr>
<th></th>
<th>Flux (erg cm(^{-2}) s(^{-1}))</th>
<th>Energy range (keV)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>On the line connecting</td>
<td>2 \times 10^{-9}</td>
<td>[0.2–0.28]</td>
<td>[6]</td>
</tr>
<tr>
<td>Ari–Tau (139°, –30°) (174°, –24°)</td>
<td>2 \times 10^{-9}</td>
<td>[0.4–1.9]</td>
<td>[7]</td>
</tr>
<tr>
<td>near λ Sco</td>
<td>(5 \times 10^{-10})</td>
<td>[0.4–1.9]</td>
<td>[8]</td>
</tr>
</tbody>
</table>


Electrons produce γ-rays by Bremsstrahlung in the interstellar gas, which would result in a γ-ray flux \(10^{3}\) times greater than that observed.

(c) Bremsstrahlung

If Bremsstrahlung of a few 100 eV electrons in the neutral interstellar gas is responsible for the observed soft X-rays, then the presence of these electrons would
also result in a rate of ionization per hydrogen atom of $\zeta_{\text{H}} = 10^{-11} \text{ s}^{-1}$, which far exceeds the limit set by the heating of the interstellar gas (e.g. Field, 1975).

(d) **Thermal Emission**

From the above discussions one can conclude that the processes (a), (b) and (c) are irrelevant for the generation of the observed soft X-ray diffuse component. Thus we are left with a thermal emission process. Indeed, the observed energy spectrum shows no sign of non-thermal processes, but is in agreement with that of the thermal emission from a thin hot plasma.

The absolute flux of diffuse soft X-rays incident upon the Earth's atmosphere is of practical use. Flux values in several reference directions, at $\frac{1}{4} \text{ keV}$, and corrected for the instrument response function are tabulated in Table III. The estimation is only slightly dependent on the assumed energy spectrum. We have used an exponential spectrum of the form, constant $\times E^{-1} \exp \left( -E/kT \right)$ (thermal Bremsstrahlung with unit Gaunt factor) with $kT = 0.20 \text{ keV}$.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Flux photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$</th>
<th>Count rate adopted from</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galactic north pole</td>
<td>370</td>
<td>Henry <em>et al.</em> (1971)</td>
</tr>
<tr>
<td></td>
<td>300 ± 30</td>
<td>Davidsen <em>et al.</em> (1972)</td>
</tr>
<tr>
<td></td>
<td>350 ± 20</td>
<td>Hayakawa <em>et al.</em> (1976)</td>
</tr>
<tr>
<td>Galactic south pole</td>
<td>180 ± 20</td>
<td>Hayakawa <em>et al.</em> (1976)</td>
</tr>
<tr>
<td>Galactic plane, anti-center</td>
<td>120 ± 15</td>
<td>Bunner <em>et al.</em> (1971, 1973)</td>
</tr>
</tbody>
</table>

The integrated energy flux values are also estimated for high-flux and low-flux regions:

$$L\text{-band} \ (0.1-0.28 \text{ keV}) \quad (1.5-3.6) \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.\quad (13)$$

$$M\text{-band} \ (0.28-1.0 \text{ keV}) \quad (0.4-2.6) \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.\quad (13)$$

As is clear from the sky maps, the high-flux and low-flux regions in different energy bands do not necessarily coincide.

### 6. Regions of Soft X-ray Enhancement

We have seen in Section 4 that the distribution of the soft X-ray diffuse background cannot be accounted for in terms of simple geometrical models. Apart from the gross feature described in Section 4, one notices in the sky maps in Figure 10 that there
exist several regions where the soft X-ray brightness is significantly larger than the surrounding area. The enhancement of the largest scale can be seen along the most prominent radio loop, Loop I (the North Polar Spur) (1). An extended region showing a pronounced enhancement in the M-band exists in the Lupus region (2) about in the middle of Loop I. On the anti-center side, there are two distinct regions of enhanced emission; one in the constellation Gemini (3), and another in the constellation Eridanus (4). These enhancements are described in detail in this section. In most of these soft X-ray enhanced regions, there seem to exist non-thermal radio features which are presumably associated with them. This evidence suggests that the enhanced soft X-ray emission is related in one way or another to supernova remnants.

An extended emission feature that runs along \( l \approx 235^\circ \) from \( b \approx -30^\circ \) towards the south galactic pole is clearly visible in the Wisconsin map (Figure 10d). This region coincides with an extended minimum of \( N_H \) \(<2 \times 10^{20} \) atoms cm\(^{-2}\). There is a very deep minimum of \( N_H \) in the region \( l \approx 140^\circ-180^\circ, b \approx 50^\circ-60^\circ \), where the hydrogen column density goes down to \( 5 \times 10^{19} \) atoms cm\(^{-2}\). This region does show a soft X-ray enhancement (Hayakawa et al., 1976). The Gemini and Eridanus enhancements also coincide with local \( N_H \) minima.

As mentioned in Section 4, although the soft X-ray enhanced regions often coincide with local \( N_H \) minima, the assumption of an extradisc component fails to explain quantitatively the observed enhancement in terms of reduced absorption and there is at present no compelling evidence for the presence of an intense extradisc component. This evidence would rather indicate that these regions are mostly ionized and filled with a tenuous hot plasma, as will be discussed later.

(1) Loop I (North Polar Spur)

The North Polar Spur is a prominent non-thermal radio feature in the northern hemisphere, which forms an arc from the galactic plane at \( l \approx 30^\circ \) towards north high latitudes. There are several other spurs; the Cetus arc (Loop II), Loop III and Loop IV. Several authors suggested that these spurs seem to follow small circles (Large et al., 1962; Quigley and Haslam, 1965; Haslam et al., 1971; Milogradov-Turin, 1970). Hanbury Brown et al. (1960) first suggested that the spurs may be old supernova remnants. Detailed radio study revealed that the weaker radio ridge continues from the North Polar Spur following a small circle and returns to the plane at \( l \sim 270^\circ \) (Berkhuijsen, 1971). This is called Loop I. Parameters of these loops are given in Table IV, taken from Berkhuijsen (1973).

Bunner et al. (1972) reported enhanced X-ray emission in the energy ranges \( E < 0.28 \) keV and 0.5 to 1 keV which seemed to be associated with the North Polar Spur. Their result is shown in Figure 11. de Korte et al. (1974) later confirmed the result of Bunner et al. Crudace et al. (1976) also detected enhanced X-ray emission during four crossings of Loop I. The X-ray enhanced region runs along the North Polar Spur with a width of 15° or larger and is located inside and close to the radio ridge. These results favored a supernova origin of Loop I.
TABLE IV

<table>
<thead>
<tr>
<th>Direction of the center</th>
<th>Diameter</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$l(\degree)$</td>
<td>$b(\degree)$</td>
</tr>
<tr>
<td>Loop I</td>
<td>329 ± 1.5</td>
<td>17.5 ± 3</td>
</tr>
<tr>
<td>Loop II</td>
<td>100 ± 2</td>
<td>−32.5 ± 3</td>
</tr>
<tr>
<td>Loop III</td>
<td>124 ± 2</td>
<td>15.5 ± 3</td>
</tr>
<tr>
<td>Loop IV</td>
<td>315 ± 3</td>
<td>48.5 ± 1</td>
</tr>
</tbody>
</table>

Fig. 11. Soft X-ray maps of the North Polar Spur region in two energy intervals in galactic coordinates (Bunner et al., 1972).

Many of the supernova remnants (SNR) are known to be X-ray sources. Some of them, like the Cyg Loop, the Vela SNR and the Puppis SNR, are strong soft X-ray emitters, whose radiation predominantly falls in the range below 1 keV. These SNR's together with the theory of the evolution of supernovae are fully discussed in the review of Gorenstein and Tucker (1976). If the above mentioned radio loops were SNR's, they are of an extraordinary scale as compared to known SNR's whose angular diameters are a few degrees or smaller.

Recently Hayakawa et al. (1976a) reported the result of an observation of Loop I, scanning from the north pole to the south pole through the center of Loop I ($l \approx 330^\circ$, $b \approx 20^\circ$). They detected the enhancements above 0.4 keV not only at the crossing of
the northern arc \((b \approx 75^\circ)\) but also at the crossing of the hypothetical southern arc \((b \approx -30^\circ)\) which is the extrapolation of the small circle to the south of the galactic plane where the radio feature is much obscured. They also showed that the energy

![Graph showing pulse-height spectra observed in directions inside Loop I (Hayakawa et al., 1976a). The solid line represents the thermal emission spectrum for a temperature of 0.10 keV, calculated for modified abundances (see 8.1.1), convolved with the instrument response function. This curve approximates the spectra observed outside Loop I by Hayakawa et al. (see Figure 26).](image)

\(b = 75^\circ \pm 63^\circ\)
\(l = 290^\circ \pm 360^\circ\)

\(b = 60^\circ \pm 45^\circ\)
\(l = 330^\circ \pm 345^\circ\)

\(b = 42^\circ \pm 33^\circ\)
\(l = 315^\circ \pm 340^\circ\)

\(b = 27^\circ \pm 9^\circ\)
\(l = 315^\circ \pm 340^\circ\)

\(b = 6^\circ \pm 0^\circ\)
\(l = 315^\circ \pm 340^\circ\)

\(b = -12^\circ \pm 27^\circ\)
\(l = 315^\circ \pm 340^\circ\)
spectrum inside Loop I consistently exhibits a hump around 0.65 keV, which disappears outside Loop I. The spectra inside Loop I are shown in Figure 12 as compared with those outside. The hump is particularly prominent in the Lupus region which is about in the middle of Loop I. Fitting of the calculated thermal emission spectrum with the observed result indicates that the hump is constituted of the emission lines of O vii (0.57 keV) and O viii (0.65 keV) as shown in Figure 13. The estimated temperature is approximately $3 \times 10^6$ K. Fe xvii lines (0.83 keV etc.) may also contribute to the hump, which would suggest a somewhat higher temperature.

Fig. 13. The pulse-height spectra for the northern arc of Loop I (a) and for the Lupus enhancement (b) fitted with a composite spectrum of two components: the emission from the Loop I shell (dashed curve) and the foreground emission (dash-dotted curve). The dashed curve represents the thermal emission spectrum for a temperature 0.27 keV, the dash-dotted curve for 0.10 keV, both were calculated for modified abundances (see 8.1.1). Interstellar absorption is neglected in (a) for the Loop I component, it is taken into account in (b) for a hydrogen column density $1.8 \times 10^{20}$ atoms cm$^{-2}$ (Hayakawa et al., 1976a).

The presence of enhancements along the northern as well as the southern arcs together with the common spectral features throughout Loop I suggests a shell-like emission region and strengthens the supernova origin hypothesis of Loop I. The over-all bright feature extending over $l \approx 330^\circ - 40^\circ$ and $b \approx -40^\circ + 70^\circ$ in the M-band map of Figure 10 is possibly due to Loop I emission.

The recent Wisconsin survey (Burstein, 1976) (see Figure 10f, g) reveals the detailed structures presumably associated with Loop I. The most remarkable features in their maps are two bright regions in the M-band (Figure 10g); one centered near $l = 20^\circ$, $b = 25^\circ$, and the other centered near $l = 0^\circ$, $b = -10^\circ$. The authors notice that the feature of the former region seems to coincide with a ring-like structure of neutral hydrogen evident in the velocity range 10–20 km s$^{-1}$ (Heiles, 1975). A pronounced peak near 0.65 keV was also observed in this region in our
recent rocket flight (unpublished). The latter region may include some contribution from discrete sources near the galactic center. They also call attention to the fact that the very intense region near $l = 0^\circ$, $b = -10^\circ$ coincide with the X-ray burster NGC6624.

Crudace et al. (1976) and Hayakawa et al. (1976a) attempt to compare their observed results with the theoretical calculation of the evolution of supernova remnants (Chevalier, 1974; Mansfield and Salpeter, 1974). In both cases the radio ridge is assumed to represent the location of the shock front. Hayakawa et al. obtained a set of parameters for the supernova remnant which can approximately reproduce the X-ray profile and the absolute luminosity assuming a distance of 130 pc (Berkhuijsen, 1973); i.e. a total energy of $3 \times 10^{51}$ ergs and an age of $1.1 \times 10^5$ yr for an interstellar density of $7 \times 10^{-3}$ hydrogen atoms cm$^{-3}$. At this stage of evolution, the dense neutral sheet would not have developed yet, in agreement with a hydrogen column density smaller than $10^{19}$ atoms cm$^{-2}$ as observed for $\alpha$Vir (Bohlin, 1975) which is supposedly located within the Loop I shell. The expansion speed of the shell is expected to be roughly 350 km s$^{-1}$ at this age, though at present there is no evidence in favor or against such a fast expansion.

Crudace et al. on the other hand, take for granted that the shock temperature is $10^6$ K and that the radiative cooling in the outer shell has already started. They consider that the neutral hydrogen ridge running parallel to the North Polar Spur along its outside is evidence for the commencement of the effective cooling. From these conditions, they estimate the age of the remnant to be between $1.4 \times 10^5$ and $3.8 \times 10^5$ yr and the energy of $1.5 \times 10^{51}$ to $4 \times 10^{53}$ ergs, according to the limits of the assumed radius $120 \pm 40$ pc and the ambient gas density $0.1-0.6$ cm$^{-3}$.

There are two major differences in the assumptions these two groups have made; i.e., (1) the shock temperature and (2) the ambient gas density. Regarding the shock temperature, $10^6$ K may be too low. As long as the condition of local thermal equilibrium holds, the evidence of intense O vii and O viii lines sets the effective temperature fairly well near $3 \times 10^6$ K, since the intensity of these lines are steeply temperature-dependent. Then this implies a shock-front temperature of roughly $2 \times 10^6$ K. On the other hand, the ambient gas density of $7 \times 10^{-3}$ atoms cm$^{-3}$ is certainly much lower than that averaged over larger distances than 100 pc, although there is clear indication for an anomalously low density of neutral hydrogen within 100 pc from the Sun (compiled by Henry et al., 1976) considering L$\alpha$ absorption measurements. Setting a shock temperature at $2 \times 10^6$ K, an increased gas density results in too large a soft X-ray luminosity. Whereas, a larger age to reduce X-ray luminosity causes too large a separation of the X-ray emitting region from the radio limb.

In connection with the apparent high temperature inferred from the oxygen lines and the very low ambient gas density required, one might as well question the condition of local thermal equilibrium within the X-ray emitting shell. Another possibility is to assume that the supernova explosion took place inside an old supernova cavity in which the gas density was already very low. This would account
for the unusually large remnant size with still a very high temperature and at the same
time the presence of the neutral gas sheet which would have been formed by the
previous supernova. The probability that a supernova explosion occurs in an old
supernova cavity is indeed not negligibly small. This would be of the order of 10\%, as
considered later, according to the presently known supernova rate (∼1/50 to
1/100 yr⁻¹) and a life time of the remnant of the order of (3–5)×10⁶ yr.

For an assumed diameter of 230 pc for the Loop I shell (Table IV), the total
luminosity is estimated to be (0.3–1)×10³⁵ erg s⁻¹ and the X-ray emitting plasma
would still carry thermal energy of the order of 10⁵¹ ergs.

Loop I is the first large scale object where clear evidence for intense emission
lines is obtained. Further investigation of these lines, in particular the intensity ratio
of O vii and O viii lines, would firmly fix the temperature of the Loop I shell.
Furthermore, it will provide an important input to the assessment of abundances of
elements of the interstellar matter.

The association of a prominent soft X-ray enhancement of large area with Loop I
suggests that a considerable part of the soft X-ray diffuse background may find its
origin in old supernova remnants, which are supposed to be numerous in the galactic
disc. This is further discussed in the following sections.

(2) The Lupus Enhancement

Published sky maps show a broad feature of soft X-ray enhancement (∼15° in
extent), centered at about b = 15°, l = 330°, which is most prominent in the M-band
(Bunner et al., 1972; Palmieri et al., 1972; Hayakawa et al., 1975a, de Korte et al.,
1976). This region of enhanced emission includes two supernova remnants, the
Lupus Loop and SN1006, the latter being identified as a hard X-ray source
(kT = 4.5×10⁷ K) by Winckler and Laird (1975). Since the emission region is
appreciably broader than the angular separation and size of these two remnants
(4.5° diameter for the Lupus radio loop, 30×22 arc min for SN1006), it seems unlikely
that the whole enhancement can be caused by these two remnants.

Hayakawa et al. (1976) report that the spectrum of the total enhancement is
similar to that of the North Polar Spur and also shows a marked peak near 0.65 keV,
indicative of a strong O vii and O viii line contribution. They consider, because of
this spectral similarity, the enhancement to belong to Loop I.

Preliminary results of a recent rocket observation of the Lupus enhancement with
an order of magnitude better angular resolution (15 arc min in one direction) shows
clearly that the enhancement comprises at least four sources (Bleeker, 1977, private
communication). The count rate profile is shown in Figure 14 superimposed on a
radio map of Milne (1971). An extended source coincides in one direction with the
Lupus SNR compatible with the angular size of the radio source.

Another peak includes SN1006 in the line of the field of view. The spectrum is
distinctly different from the extended source which covers the Lupus SNR, indicating
a temperature in excess of 10⁷ K. The energy spectrum shows a low energy cut-off
which is not incompatible with distance estimates to SN1006 derived from: optical
and radio observations ranging from 1.3 to 4.9 kpc (Minkowski, 1966; Milne, 1970; Downes, 1971). On the other hand the observed intensity in the harder X-ray range (>1 keV) appreciably exceeds the value derived by Winckler and Laird.

The identification of this source with SN1006 therefore needs some reservation, one of the radio bright spots of the Lupus loop might also contribute to the observed peak.

Two additional, possibly extended sources, are present which are as yet unidentified. The spectrum of the Lupus SNR region shows a pronounced peak in the M-band, very similar to Loop I. The unidentified sources also show a similar spectral feature. The distance to the Lupus radio loop is estimated to lie between 400 and 600 parsec (Ilovaisky and Lequeux, 1972). The structure of this radio source is much alike the Cyg Loop and Vela X, supernova remnants similar in size and probably age to Lupus. With these assumptions, the intrinsic X-ray luminosity of the Lupus loop
would be more than an order of magnitude smaller than the other two remnants and amounts to at most $3 \times 10^{34}$ ergs s$^{-1}$.

(3) *The Monoceros-Gemini Enhancement*

A broad region of soft X-ray enhancement is present in the Monoceros-Gemini constellations centered near $l = 205^\circ$, $b = 20^\circ$ (see Figure 10). This enhancement was first observed at $E < 0.28$ keV by Bunner *et al.* (1971). Further observations of this sky region were included in the measurements of Yentis *et al.* (1972), Davidsen *et al.* (1972), Bunner *et al.* (1973), Garmire (1975), Williamson *et al.* (1974) and Zwijnenberg (1976) with typical angular resolutions of several degrees. Figure 15 shows the intensity distribution of soft X-rays for a sky strip near $l = 200^\circ$ as given by Zwijnenberg (1976). The enhancement is clearly visible in both the L-band ($E < 0.54$ keV) and above ($0.54 < E < 2$ keV) and is certainly extended considering the angular resolution of the experiment ($\approx 3^\circ$ in the $b$-direction). This excludes a dominating contribution of a discrete source like e.g. U-Geminorum ($l = 198.8^\circ$, $b = 22.8^\circ$) which was suggested by Warner (1974). Also, no correlation of the observed enhancement with the Monoceros Nebula, possibly an old SNR, was found (Zwijnenberg, 1976).

A local minimum in $N_H$ shows up clearly as an extended region of about $10^\circ$ diameter centered at $l = 214^\circ$, $b = 20^\circ$ on the low-velocity hydrogen map of Heiles and Jenkins (1976) with $N_H = 2 \times 10^{20}$ hydrogen atoms cm$^{-2}$ (Heiles, 1975). This region coincides at least partly with the soft X-ray feature.

The association of non-thermal radio spurs with large-scale soft X-ray intensity enhancements is promisingly shown for the case of the North Polar Spur. Berkhuysen (1973) suggested that the Gemini enhancement could also be associated with a radio spur, observed at 150 and 820 MHz, centered on the line $l = 195^\circ$, $b = +8^\circ$ to $l = 202^\circ$, $b = +30^\circ$. The alleged radio spur shows up most clearly in a recent photograph generated by Heiles and Jenkins (1976) from the 820 MHz radio-continuum survey conducted by Berkhuysen (1972). Williamson *et al.* (1974) noticed that this spur like feature might extend south of the galactic plane to $l = 205^\circ$, $b = -15^\circ$. The X-ray enhancement observed by Williamson *et al.* and by Zwijnenberg south of the plane extends to $b = -5^\circ$ but does not exhibit any significant relation with this or other radio continuum structures. The energy spectrum indicates thermal emission for a Bremsstrahlung temperature of about $3 \times 10^6$ K for the Gemini enhancement (Garmire, 1975; Williamson *et al.*, 1974).

(4) *The Eridanus Enhancement*

The soft X-ray brightness distribution of the southern galactic hemisphere shows a pronounced brightness enhancement which is located in the constellation Eridanus centered near $l = 204^\circ$, $b = -38^\circ$ (Figure 10d). This region also coincides with a local minimum of neutral hydrogen with $N_H \approx 4 \times 10^{20}$ atoms cm$^{-2}$. Its presence was already evident from the survey of Davidsen *et al.* (1972) and was further investigated by Garmire (1975), Williamson *et al.* (1974), Naranan *et al.* (1976) and
Zwijnenberg (1976). The enhancement is most pronounced in the L-band and has a half-power width of approximately 15°, and the energy spectrum appears similar to the Gemini enhancement. According to Naranan et al. (1976) the source flux of the enhancement, corrected for interstellar absorption, amounts to $5 \times 10^{-9}$ erg cm$^{-1}$ s$^{-1}$ between 0.2 and 1 keV. Zwijnenberg (1976) derives a flux which is about three times lower, which is not too surprising considering the ambiguity in determining the excess flux over that in adjacent regions.

The Eridanus region contains a number of interesting large scale features which could be physically associated with the X-ray emitting region like an Hα nebulosity complex and neutral gas velocity features (Zwijnenberg, 1976). Figure 16 shows a map of the Eridanus region for two X-ray energy bands, in which the soft X-ray data of Naranan et al. (isophotes) and Zwijnenberg (histograms) are superimposed. In addition large-scale features are indicated together with other relevant astronomical objects. The radio pulsar MP 0450 shows an anomalously large dispersion measure, and the UV-star HD 28497 at 445 pc shows O vi absorption, both of which are indicative of the presence of a hot gas component. Naranan et al. considering the possible association of the X-ray enhancement with the bright circular Hα filament centered at $l = 190°$, $b = -45°$ and the large similarities of the object with the Cygnus Loop and Vela-X SNR's interpret the enhancement as an old SNR (age $> 10^5$ yr) at a distance of about 200 pc. This distance would mean an intrinsic soft X-ray luminosity for the source of $5 \times 10^{34}$ erg s$^{-1}$.

Fig. 16. The Eridanus enhancement in the L-band (a) and M-band (b). Isophotes: X-ray data of Naranan et al. (1976), histograms: X-ray data of Zwijnenberg (1976). Several other features are shown: Hα-complex (dotted regions), H I velocity shift (vertically shaded) and a region of H II emission (horizontally shaded). The positions of the radio pulsar MP0450, the UV-star HD28497 and the hard X-ray source 3U0431-10 are also given.
The count rate profiles given by Zwijnenberg, from an experiment with improved angular resolution (3° rather than the 7° of Naranan et al.), indicate that the peak emission in the L-band (see Figure 16) is not consistent with such an association. The peak X-ray brightness rather appears to coincide with the region where the large Hα-filaments meet. The Eridanus region might form an example of a complex of interacting supernova remnant shells as described by Cox and Smith (1974, see Section 7), however much more detailed observations with enhanced spatial resolution are needed to verify such a picture.

7. Hot Regions in the Interstellar Space

Until recent years, it has been generally accepted that the bulk of the interstellar medium consists of two phases: a cool phase at a temperature of roughly 100 K, and a hot phase of a temperature near $10^4$ K. These two phases are considered to be under pressure equilibrium hence in thermally stable configuration (e.g. Field, 1974). The situation thus far is summarized in Table V, as given by Hayakawa (1976). The dark clouds and the emission nebulae occupy only a small volume of the interstellar space.

<table>
<thead>
<tr>
<th>TABLE V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Dark clouds</td>
</tr>
<tr>
<td>Diffuse clouds</td>
</tr>
<tr>
<td>Intercloud</td>
</tr>
<tr>
<td>Emission nebulae</td>
</tr>
</tbody>
</table>

Recent evidence of the interstellar O VI absorption and the galactic origin of the soft X-ray background with its alleged thermal nature lead one to suspect the presence of a new higher temperature phase of the interstellar medium between $2 \times 10^5$ K and over $10^6$ K.

7.1. INTERSTELLAR O VI ABSORPTION

Direct evidence for the existence of such hot regions in interstellar space has recently been obtained from the far ultraviolet observations. Rogerson et al. (1973) first observed the absorption of O VI (lithium-like ion) in stellar spectra by the spectrometer aboard the Copernicus satellite. Further results have been published by Jenkins and Meloy (1974), York (1974) and Jenkins (1976). O VI absorption comprises two resonance lines at 1031.945 Å and 1037.627 Å from bright hot stars. In most of the stars observed, significant O VI absorption was detected. The ionization fraction of O VI, which is the ratio $n$(O VI)/$n$(O), is shown in Table VI calculated by Shapiro and Moore (1976). It reaches maximum at $3 \times 10^5$ K and falls off towards higher
temperature. Since the ionization by X-rays is taken into account in their calculation, the temperature dependence above $10^6$ K becomes less steep than otherwise.

Thus the \( \text{O\,vi} \) absorption provides an unequivocal evidence for the presence of such high temperature regions in space. The observed \( \text{O\,vi} \) column densities versus distance to the stars is shown in Figure 17, the data are taken from Jenkins (1976). Although there is a trend that the \( \text{O\,vi} \) column density increases roughly in proportion to the distance, individual values scatter widely over an order of magnitude.

One important point of discussion concerns the origin and distribution of these \( \text{O\,vi} \) ions. Jenkins and Meloy (1974) conclude that these \( \text{O\,vi} \) ions are widespread in interstellar space primarily because the radial velocities of the stars and of the \( \text{O\,vi} \)
are not correlated with each other. They derived the mean space density of O vi to be

\[ \langle n(\text{O vi}) \rangle \approx 1.7 \times 10^{-8} \text{ cm}^{-3}. \] (14)

On the other hand, Castor et al. (1975) argued that the observed O vi may originate from a hot plasma sphere around some early-type stars which possess intense stellar winds. This is discussed in the next subsection.

7.2. FORMATION OF A HOT INTERSTELLAR PLASMA

Cox and Smith (1974) proposed that supernova explosions at the presently known rate would generate and maintain a mesh of interconnected tunnels containing a hot plasma at a temperature \( \sim 10^6 \) K in the interstellar space. Their estimate shows that such high temperature regions could occupy a considerable fraction of the interstellar volume.

Suppose the isolate cavities of supernova remnants (SNR) occupy a fraction \( q \) of the interstellar volume,

\[ q = \tau r \text{V}_{\text{SNR}}, \] (15)

where \( r \) is the supernova rate per unit volume, \( \tau \) the mean life time before a remnant disappears, and \( \text{V}_{\text{SNR}} \) the volume of a cavity. They assume the supernova rate of one per 80 yr per galaxy, and a mean life time \( \tau = 4 \times 10^6 \) yr. The number of existing supernova remnants would then be approximately \( 5 \times 10^4 \). If the mean radius of the SNR cavity is taken to be 40 pc, \( q \) amounts to 10%. Then a chance that a new supernova explosion occurs in the existing cavity is 0.1 and that a new shell hits the nearest cavity and eventually intersects would be as large as 0.55. Once they intersect, the shock wave propagates fast through the low density interior of an old cavity and reheats it. Cox and Smith concluded from a Monte Carlo calculation that these cavities would eventually form a tunnel network which is filled with thin plasma of temperature \( \sim 10^6 \) K, occupying possibly half the interstellar volume.

Further extensive re-examination was made by Smith (1976) with more elaborated simulations. It essentially confirmed the previous results. The result of his Monte Carlo calculation is shown in Figure 18. The figure indicates that the fraction of the volume occupied by hot tunnels significantly increases by interconnections and reheating of SNR cavities for \( q > 0.1 \) as compared with the filling factor, \( f = 1 - e^{-q} \), when the interconnection and reheating would not occur. The former is probably the case with the presently estimated rate of supernova explosions. According to Smith's result, however, the increase of the filling factor of hot regions by interconnection and reheating of supernova cavities may not be as dramatic as Cox and Smith previously suggested.

Quite a different idea was put forward by Castor et al. (1975) who pointed out that a hot plasma sphere may be formed around early type stars if a strong stellar wind exists. The stellar wind with a velocity \( v \) and a mass loss rate \( \dot{M} \) forms an expanding
shell which is similar to the supernova remnants. The radius of the shell is given by

$$R_s(t) = 28 (\dot{M}_6 v_{2000}^2 / n_0)^{1/5} t_6^{3/5} \text{ pc},$$

(16)

where $\dot{M}_6 = \dot{M} / 10^6 M_\odot \text{ yr}^{-1}$, $v_{2000} = v / 2000 \text{ km s}^{-1}$, $n_0$ is the density of the ambient gas in cm$^{-3}$ and $t_6$ is the age in $10^6$ yr. The temperature of the shock-heated region is

$$T_s(t) = 1.6 \times 10^6 n_0^{2/35} (\dot{M}_6 v_{2000}^2)^{8/35} t_6^{-6/35} \text{ K},$$

(17)

which is little dependent on the parameter values assumed.

Consequently, 'hot bubbles' are formed with a typical radius of 30 pc and a temperature of $10^6$ K. According to Hutchings (1976) the mass loss rate is large when $M_v < -6$. Such stars will have a short time scale of evolution less than $10^7$ yr. The space density of such stars is roughly estimated to be $2 \times 10^{-9} \text{ pc}^{-3}$. This gives a filling factor,

$$f = 2 \times 10^{-4},$$

Hence, the filling factor of these hot regions is two to three orders of magnitude less than the value the supernova remnants would have. However, great uncertainty still exists in the estimate of the space density of stars responsible for the hot bubble formation in this mechanism. Castor et al. claim that the O vi column density of such a bubble will amount to

$$N(O \text{ vi}) = 1.5 \times 10^{13} n_0^{9/35} (\dot{M}_6 v_{2000}^2)^{1/35} t_6^{8/35} \text{ cm}^{-2},$$

(18)

which is essentially in the range of the observed values.
Decisive evidence for this model will be obtained by the observation of soft X-ray emission from these early type stars, since a substantial part of the emission falls in the soft X-ray region. The X-ray luminosity is expressed by

$$L_x = 3.8 \times 10^{33} n_0^{18/35} (M_2 v_{2000})^{37/35} \nu_6^{16/35} \text{ erg s}^{-1}. \tag{19}$$

Unfortunately, nearby stars have small mass loss rate. So far, no positive observation is available which identifies the hot bubble produced by a high-velocity stellar wind.

8. Distribution and Energy Spectrum of the Soft X-Ray Diffuse Background

The available results on a detailed analysis of the energy spectrum are rather scanty, because of the reasons, as discussed in Section 3, i.e., (1) deformation of the incident spectrum by the window transmission characteristics and (2) a poor energy resolution of the detector in the energy range concerned. Despite these technical limitations, important implications have emerged from recent observational results. The 'multi-color' method was described in Section 3.1, which provides a very useful mean to represent the characteristics of the energy spectrum. We shall begin with the discussion of results in the 'multi-color' representation, and then proceed on results of more detailed spectral analyses.

8.1. Observational results in 'multi-color' representation

de Korte (1975) and de Korte et al. (1976) introduced a three-color representation for the first time, employing the L-band (0.18–0.4 keV), M-band (0.4–0.8 keV) and H-band (0.8–1.8 keV). As shown in Figure 19 the variation of the spectrum in different parts of the sky is evident. A measured pulse height spectrum is represented by a point on the diagram. The points with the same M/L ratio lie on a 45° line. If the spectrum hardens (larger M/L ratio), the 45° line shifts accordingly to the left. It can be seen that the galactic pole region and a part of the plane (l = 100–130°) have roughly the same M/L ratio, whereas the enhanced region along the North Polar Spur and the Lupus enhancement show a much larger M/L ratio.

Hayakawa et al. (1976b) presented the M/L ratio over their scan path along a great circle perpendicular to the galactic plane following the galactic meridians of l = 150° and 330°. This is shown in Figure 20. The M/L ratio is markedly larger inside Loop I than outside. The authors note that M/L inside Loop II is also significantly large. Excluding Loop I and Loop II, the rest of the scanned strip shows almost a constant M/L value. This therefore indicates that, while the intensity varies, the shape of the spectrum changes little in this sky strip. As discussed in Section 6, large M/L inside Loop I is due to a prominent hump which is most probably caused by emission lines of O VII and O VIII.

A similar representation is given by Burstein et al. (1976) for the sky region including the North Polar Spur (Figure 10f, g). Figure 21 shows their map of M/L.

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Remarkable excess in the M-band in two ‘hot spots’ are clearly shown (see 6(1)). Note that the absolute values are not comparable with these of Hayakawa et al., since the transmission characteristic of their detectors are appreciably different from each other.

Burstein et al. also employed the band fraction representation. They employ three pass bands, namely those below the K-absorption edges of boron (B-band) and carbon (C-band), and one above the K-absorption edge of carbon (M-band). Pulse height ranges are 60–400 eV for boron-coated Formvar and for Kimfol, and 400–850 eV, respectively. Their band fractions are defined as follows: Let \( R_T = R_B + R_C + R_M \) be the sum of the counting rates in each of the pass bands. \( f_B = R_B/R_T \), \( f_C = R_C/R_T \) and \( f_M = R_M/R_T \) are the band fractions. For further analysis they adopt \( f_B \) and \( f_M \) to represent a spectrum.

Though qualitative, these hardness ratios M/L and band fraction analysis lead to important implications about the galactic soft X-ray emission, as discussed in what follows.
Fig. 20. The top figure shows the observed ratio of the M-band (0.5–0.8 keV) rate to the L-band (0.16–0.3 keV) rate, over a great circle along the galactic meridians at $l = 150^\circ$ and $330^\circ$ (Hayakawa et al., 1976b). The galactic coordinates are indicated along the top line. Regions corresponding to Loop I and Loop II are marked in the figure. The bottom figure indicates, for comparison, the hydrogen column density $N_H$ along the same scan path as above, taken from Heiles (1976) and Daltabuit and Meyer (1972).

Based on the hypothesis that the soft X-ray diffuse background originates from a high temperature plasma in interstellar space, the following models for the distribution of the emission regions can be considered.

1. **Case A**: A localized emission region with intervening cool matter.

   The spectrum is expressed by

   \[ I(E) = \frac{\Lambda(T, E)}{4\pi} n_e^2 R \, e^{-\sigma(E) N_H}, \tag{20} \]

   where $\Lambda(T, E)n_e^2$ is the volume emissivity of a plasma with electron density $n_e$, $R$ the extent of the X-ray emitting region and $N_H$ the column density (hydrogen atoms cm$^{-2}$) of the intervening neutral gas.
(2) Case B: Emission regions with electron density \(n_e\), interspersed in neutral interstellar matter.

The spectrum is approximately given by

\[
I(E) = \frac{\Lambda(T, E)\langle n_e^2 \rangle}{4\pi\sigma(E)\langle n_H \rangle} (1 - e^{-\sigma(E)N_H}),
\]

where \(\langle n_e^2 \rangle = fn_e^2\), \(f\) being a filling factor of the X-ray emitting plasma, and assuming a constant temperature \(T\) for all emission regions.

For \(\Lambda(T, E)\), a thermal Bremsstrahlung (free-free) spectrum (see Equation (5)) is often utilized. This spectrum should be taken as an empirical formula, since the thermal emission from a thin hot plasma consists of mostly emission lines in the temperature range below \(kT = 1\) keV. However, it can be shown that the pulse height spectrum of the thermal emission is pretty well approximated by that of thermal Bremsstrahlung with an appropriate temperature for the presently available energy resolution.

More realistically, \(\Lambda(T, E)\) includes line emission and radiative recombination together with thermal Bremsstrahlung for assumed abundances of elements. Theoretical calculations for \(\Lambda(T, E)\) have been published in the literature (see Section 2.2).

8.1.1. Abundances of Elements

\(\Lambda(T, E)\) is dependent on the abundances of elements in the plasma, since most of the emission consists of lines from elements at various ionization states determined by the temperature, if collisional equilibrium is assumed to hold.
For cosmical (or solar) abundances (e.g. Allen, 1973), the important contributing elements to the L-band emission around $10^6$ K are iron, silicon, sulphur, magnesium and neon, while in the M-band oxygen contributes most. At higher temperatures, the M-band emission increases sharply due to emission lines from oxygen, iron and neon.

However, the abundances of elements of the interstellar medium are still pretty uncertain. Much of the information of the interstellar abundances has become available from the Copernicus UV observations (Spitzer and Jenkins, 1975). Of particular interest is the detailed analysis of the interstellar absorption lines appearing in the spectra of $\zeta$ Oph (Morton, 1975). The result shows that many elements are depleted by different factors with respect to cosmical abundances, as shown in Figure 22. Carbon and other metallic elements may be concentrated in the form of interstellar dust grains. The measured depletion factors also differ considerably for different stars. Furthermore, the effect of sputtering and evaporation from dust grains (Burke and Silk, 1974; Aanestad, 1973) add more complication to the assessment of the actual element abundances in the hot plasma concerned.

Burstein et al. (1976) adopted cosmical abundances and those for $\zeta$ Oph as two extreme cases, for an intermediate case they assume that nitrogen and oxygen are not depleted. Such a volatile element is assumed to exist in gaseous form in a high temperature plasma.

Hayakawa et al. (1976a, b) employ modified abundances derived from the $\lambda$ Sco UV-observation (York, 1975), the nearest star studied for the interstellar absorption, with the exception of oxygen for which they assume no depletion. The large

![Graph](image)

Fig. 22. Composition of H I clouds in the direction of $\zeta$ Oph relative to the Sun. Elements lying below the horizontal line are depleted compared with their solar abundance, the length of the vertical bars indicate experimental uncertainties (Morton 1975).
depletion factor of oxygen (three to five) observed in UV absorption could be understood if a major part of oxygen is in the state of O II, considering that a large abundance of N II was observed (Morton, 1975) and the ionization potential of oxygen is smaller than that of nitrogen. For the modified abundances, sulphur is the main contributor in the L-band and, hence, the shape of the spectrum below 0.4 keV becomes less sensitive to the temperature than it is for cosmical abundances.

8.2. Multi-temperature interpretation

Burstein et al. analysed band fraction diagrams $f_B$ vs $f_M$ for Case A and Case B, utilizing the spectrum of Raymond et al. (1976). For each of the cases with given abundances, the computed set of $(f_B, f_M)$ follows a trajectory with varying temperature. Examples are shown in Figure 23. Points on the $f_B$ vs $f_M$ diagram for the measured spectra in the observed sky region (Figure 10f, g) are confined within an elongated contour. Data from most regions of the sky observed tend to fall within the bottom part of this contour, whereas the data from the regions which are most prominent in the M-band tend to fall within the upper part of the contour.

The result shows that none of the computed band fraction curves enters the contour enclosing the observed data points. The single exception is Case A with $N_{HI} = 0$ and with fully depleted abundances for $T > 10^{6.4}$ K. This exceptional case, however, predicts too high a counting rate above 0.85 keV to be compatible with the observed rate. Thus the authors conclude that a single temperature component is not in agreement with the data and that multi-temperature components are required.

Suppose several regions of temperature $T_1$, $T_2$, etc. contribute with counting rates $R_1$, $R_2$, etc., the resultant band fraction $f_R$ is then given by

$$f_R = \frac{\sum f_i R_i}{\sum R_i},$$

where $f_i$ is the band fraction of the component from the region $i$. For a simple example, where only two regions of $T_1$ and $T_2$ contribute, the resultant point on the band-fraction diagram is on a line connecting the points for $T_1$ and $T_2$ on the band-fraction trajectory, and is located at the center of gravity determined by the 'weights' $R_1$ and $R_2$ at $T_1$ and $T_2$, respectively. The conclusion of Burstein et al. is that at least one high temperature component ($T_h > 10^{6.3}$ K) and one low temperature component ($T_l < 10^{6}$ K) are required, in order to reproduce the observed set $(f_B, f_M)$. This method cannot uniquely determine the temperatures of the respective components, however.

As a matter of fact, more than half of the sky surveyed by Burstein et al. includes Loop I. Hayakawa et al. (1975a) also concluded that the spectrum inside Loop I cannot be fitted with any spectrum of Case A or B if a single temperature component is assumed. From the evidence for probable O vii and O viii emission lines, one component of a temperature of approximately $3 \times 10^6$ K is required for Loop I (see 6(1)) together with another component of lower temperature.
Fig. 23a. Band fraction diagrams given by Burstein et al. (1976) for Case A (X-rays from localized emission region absorbed by cold intervening gas of column density $N_H$), assuming cosmic abundances and depleted abundances. Log $T$ values of the calculated thermal emission spectra are indicated on the solid line trajectory. The elongated contour indicates the area which contains almost all the diffuse background data points.
Fig. 23b. Band fraction diagrams similar to (a) but for case B with \( N_H = \infty \) (hot regions with interspersed cold absorbing gas). (a) normal abundances, a few representative data points are also shown, (b) depleted abundances, lines of constant spectral hardness are also given.

de Korte (1975) and de Korte et al. (1976) analysed the pulse height spectra taken in various regions of the sky over a larger latitude range (Figure 10b) with counters equipped with 1 \( \mu \)m and 3 \( \mu \)m thick polypropylene windows. The observed spectra are shown in Figure 24. They subdivide the spectrum in two pulse height intervals, 0.14–0.40 keV and 0.45–1.6 keV. Both parts of each spectrum are independently fitted to model spectra according to Case A and Case B.

As source spectra they used free-free emission as well as thermal emission calculated by Landini and Fossi (1970). Their major conclusion is that at least two components of different temperature are required to explain the observed spectra both in the galactic plane and the north pole regions, since the low energy portion of the spectrum yields systematically a lower temperature than that derived for the high energy part, irrespective whether Case A or B is assumed.

This led them to a model that an arbitrary line of sight always intersects several emission regions of different temperatures and that the high temperature regions dominate the high energy portion of the spectrum and vice versa. The temperatures estimated from the low- and high-energy parts of the spectra are tabulated in Table VII.

Levine et al. (1976a, b) analysed the spectral data obtained by rocket experiments with an X-ray concentrator and a proportional counter equipped with half a micron thick polypropylene, covering an energy range 90–280 eV. They noticed that the shape of the spectrum differed little over a wide southern latitude range. They fitted the observed pulse height spectra with the thermal emission spectrum calculated by Raymond et al. (1976), based on Case B but taking \( N_H \) as a free parameter. Note that it reduces to Case A with \( N'_H = 0 \), in the limit \( N_H \) approaches zero. The result is
Fig. 24. Measured soft X-ray spectra in six latitude strips in the range $-60^\circ < b < 90^\circ$ (de Korte et al., 1976). Data from two different counter systems (1 $\mu$m and 3 $\mu$m entrance windows) are given, corrections for detector background and the extragalactic hard X-ray background have been applied.

shown in Figure 25. Their result is consistent with the thermal emission from a hot plasma with a temperature $\sim 7 \times 10^5$ K. This is consistent with the result of de Korte et al. as far as the low energy part of the spectrum is concerned.
TABLE VII

|                | Galactic plane, $|b|<10^\circ$ ($10^6$ K) | North galactic pole, $b>60^\circ$ ($10^6$ K) |
|----------------|---------------------------------|-----------------------------------------------|
|                | Free-free                       | Thermal$^b$                                    |
| Low-temperature component | 0.35–0.75                       | <1.0                                            |
| High-temperature component | >3.5                            | 2.0–3.1                                        |
|                | Free-free                       | Thermal$^b$                                    |
|                | >0.45–0.70                      | <1.0                                            |
|                | none                            | 1.5–2.2                                        |

$^a$ Spill-over from the M-band into the L-band is not taken into account.

$^b$ Thermal emission spectrum computed by Landini and Fossi (1970) was employed.

Fig. 25. Spectral fits obtained by Levine et al. (1976b) over a wide range in southern galactic latitude. The analysis applies to case B but with $N_H$ as a free parameter, two different source models have been considered: exponential spectrum (a) and thermal emission from a hot plasma (b). The size of the hatched regions, indicating the allowable range of $N_H$, $kT$ combination, mainly arises from systematic errors in the experiment.

It is to be noted that Yentis et al. (1972) and Cash et al. (1976) reported a much softer spectrum in the L-band. Apart from a large intensity discrepancy relative to each other, they both obtained a very steep rise towards 0.1 keV, which indicates a lower temperature than $3 \times 10^5$ K or the presence of an intense line (or lines) near 0.1 keV. However, since Levine et al., with a similar instrument and a larger window transmission near 0.1 keV, did not observe this feature, this discrepancy remains to be solved.

8.3. A LOCAL HOT REGION

Hayakawa et al. (1976) also attempted to fit the observed pulse height spectrum above 0.1 keV obtained with 1 $\mu$m-thick polypropylene windows. As mentioned
earlier, the spectra inside Loop I cannot be fitted with a single temperature component. The spectra outside Loop I along the galactic meridians $l \approx 150^\circ$ and $330^\circ$ are shown in Figure 26. These spectra are remarkably similar to each other except for some deviation in the spectra inside Loop II. This feature is characterized by the constancy of the $M/L$ ratio in Figure 20.

An important implication is that the observed constancy of $M/L$ is incompatible with the assumption of Case B. It can be easily seen that the $M/L$ ratio in Case B is strongly dependent on $N_H$ since $\sigma(E)$ varies like $E^{-3}$ (apart from the $K$-absorption edge of oxygen at 0.53 keV). From Equation (21), the M-band intensity keeps increasing with $N_H$ practically up till $(1 - 3) \times 10^{21}$ atoms cm$^{-2}$, one optical depth for the M-band X-rays, whereas the L-band intensity saturates for nearly 10 times less $N_H$ values. Their field of view crossed a deep minimum of the neutral hydrogen column density at $b = 45^\circ - 57^\circ$ and $l \approx 150^\circ$, where $N_H \approx 5 \times 10^{19}$ atoms cm$^{-2}$.
'H i-hole' and the galactic plane, where \( N_H > 3 \times 10^{21} \) atoms cm\(^{-2} \), show essentially the same M/L ratio within the statistical uncertainties. Whereas, under the assumption of Case B, one would expect a much larger M/L value for the plane by more than a factor of 5 relative to the 'H i-hole'. This discrepancy cannot be reconciled unless one assumes extremely odd temperature and density distributions of the hot gas in the disc. Hayakawa et al. conclude that Case B, in its simple format, is not a relevant model at least in the sky region they scanned. It is still possible, and indeed more likely, that distant hot regions exist but with either a lower temperature \((T < 8 \times 10^5 \) K\) or with an electron density in the plasma appreciably smaller than \(10^{-2} \) cm\(^{-3} \), as discussed later. On the other hand, the observed constancy of M/L suggests that Case A applies for most part of the soft X-rays in this sky region.

Hayakawa et al., therefore, fitted the model spectra in the frame of Case A, taking \( kT \) and \( N_H \) as free parameters, for three different models for \( \Lambda (T, E) \): (1) a free-free emission spectrum, (2) a thermal emission spectrum with cosmical abundances, and (3) with partially depleted abundances with depletion factors, three for carbon, ten for silicon and magnesium, and twenty for iron (see discussion on abundances of elements). The thermal emission spectrum computed by Kato (1976) was employed. Except for two sky bins inside Loop II, the observed spectra in all other sky bins are in good agreement with a single temperature component. The best fit \( kT \)'s are obtained for \( N_H \) all practically zero \((\leq 10^{19} \) hydrogen atoms cm\(^{-2} \)), with 90% confidence limits of \(5 \times 10^{19} \) atoms cm\(^{-2} \) or smaller. The best fit \( kT \) values for consecutive sky regions are shown in Figure 27.

The \( kT \)-values of 0.10 keV for partially depleted abundances and 0.13 keV for cosmical abundances are somewhat larger than those derived by de Korte et al. and by Levine et al. from data below 0.3–0.4 keV. As a matter of fact, the data of Hakayawa et al. are in good agreement with theirs in the energy range below 0.4 keV. A part of this discrepancy could be due to the differences in the thermal spectra they employed. Eventually, the presence of another component of somewhat lower temperature with a constant fraction cannot be excluded from the data of Hayakawa et al., since it does not conflict with the observed constancy of the spectral shape. On the other hand, determination of temperature from the pulse height spectrum in the L-band only is subject to some uncertainty because of an insufficient bandwidth and a poor energy resolution in particular in this energy range.

That the shape of the spectrum remains constant over a wide latitude range is an important conclusion. This fact together with negligible absorption by intervening cold gas leads to the hypothesis that the solar system is within a region which is for the most part occupied by hot plasma with a temperature of approximately \(10^6 \) K.

Recent Copernicus results on \( L_\alpha \) absorption measurements indicate that the neutral hydrogen density within 100 pc of the Sun is anomalously low. Henry et al. (1976) compiled data as given in Table VIII. The average neutral hydrogen density within this region seems to be \((1-3) \times 10^{-2} \) atoms cm\(^{-3} \), although the available data are rather scanty. This evidence is in agreement with the interpretation that the solar system is within a local 'hot bubble'. The residual neutral hydrogen may be
Fig. 27. The best fit temperatures in $kT$ (keV) for consecutive sky bins determined for each spectrum of Figure 26. Three different model spectra are employed: free-free emission (open circle), thermal emission for cosmic abundance (full circle), and idem for modified abundances (cross) (see 8.1.1) (Hayakawa et al., 1976b).

accounted for in terms of localized dense sheets which cooled off quickly (Mckee and Cowie, 1975).

As mentioned earlier, the spectra inside Loop 1 obviously require at least two components of different temperature. Indeed, they can be well explained in terms of a composite of two components: one with $kT \approx 0.3$ keV representing the SNR-shell radiation and another with the same $kT$ as outside Loop 1 representing the ‘foreground’ radiation from the local hot bubble. This was shown in Figure 13.

With a different approach, Kraushaar and colleagues (1977) also arrived at the hypothesis that the solar system is inside a hot plasma region. They searched for
TABLE VIII
Interstellar neutral hydrogen densities as derived from stars closer than 100 pc

<table>
<thead>
<tr>
<th>Star</th>
<th>Distance (pc)</th>
<th>( n_H ) (cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha ) CMi</td>
<td>3.5</td>
<td>0.015–0.030</td>
</tr>
<tr>
<td>( \beta ) Gem</td>
<td>10.7</td>
<td>&lt;0.15</td>
</tr>
<tr>
<td>( \alpha ) Boo</td>
<td>11.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>( \alpha ) Aur</td>
<td>14</td>
<td>0.01–0.025</td>
</tr>
<tr>
<td>( \alpha ) Tau</td>
<td>20.8</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>( \alpha ) Leo</td>
<td>22</td>
<td>0.02</td>
</tr>
<tr>
<td>( \sigma ) Eri</td>
<td>28</td>
<td>0.07</td>
</tr>
<tr>
<td>( \alpha ) Pav</td>
<td>63</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>( \alpha ) Sgr</td>
<td>80</td>
<td>&lt;0.12</td>
</tr>
<tr>
<td>( \alpha ) Vir</td>
<td>99</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>( \beta ) Cen</td>
<td>99</td>
<td>0.11</td>
</tr>
</tbody>
</table>

correlation of the soft X-ray intensity with \( N_H \) in strips of fixed galactic latitude, employing two different passbands in the L-band: the carbon band (<0.28 keV) and the boron band (<0.18 keV). Near the galactic plane no clear correlation was found, but at intermediate latitudes they observed evident correlation indicating a constant soft X-ray intensity in both pass bands out to \( N_H = (3–4) \times 10^{20} \) atoms cm\(^{-2}\) and an intensity drop-off with further increasing \( N_H \). The fact that the observed drop-off in the boron and the carbon band occurs at about the same value of \( N_H \) is inconsistent with absorption by intervening cold gas (case A), since the boron band absorption cross-section is larger by about a factor five than that for the carbon band, whereas case B would not account for the observed drop-off.

The observed feature can be understood with a picture that a part of the ‘original’ gas with column density \( N_0 \) is displaced by an X-ray emitting plasma whose domain includes the solar system. The soft X-ray intensity would then be proportional to \((N_0 - N_H)\), the intensity drop-off is interpreted as due to less displacement of the neutral gas, thus reflecting an asymmetry of the plasma region with respect to the Sun. On account of the large absorption cross-section of the boron band X-rays, the emission of the observed X-rays should originate within \( N_H = 10^{20} \) atoms cm\(^{-2}\) to explain the similarity of the carbon and boron band data.

This Wisconsin interpretation is entirely in agreement with that of Hayakawa et al. based on the constancy of the spectral shape with an intervening gas of less than \( 5 \times 10^{19} \) cm\(^{-2}\).

In this hot bubble model, with a bold assumption that the contribution from more distant regions can be neglected at least in the L-band, the directional intensity of soft X-rays is proportional to the emission measure \( n_H^2 R \) of the local hot bubble. Figure 28 shows a polar diagram of the count rate in the L-band (0.16–0.3 keV) on a great circle along \( l \approx 150^\circ \) and 330° by Hayakawa et al. (1976b). In the direction outside Loop I, it is therefore considered proportional to the emission measure of the local...
Fig. 28. Polar diagram of the L-band (0.16–0.3 keV) intensity (counts cm$^{-2}$ s$^{-1}$ sr$^{-1}$) along a great circle which follows the galactic meridians at $l \approx 150^\circ$ and $330^\circ$. The directions of the arcs of Loop I and Loop II are marked by arrows, the southern arc of Loop I and the northern arc of Loop II are however hypothetical (Hayakawa et al., 1976b).

hot bubble. Whereas, in the direction within Loop I, it comprises the contribution from the hot bubble as well as that from the Loop I shell. Similar situations may be present in the direction of Loop II. Hence, in these directions, it represents the upper limits of the emission measure of the local hot bubble.

Such a polar diagram would depict a rough idea of a cross-section of the local hot bubble, assuming a constant average electron density. It is interesting to conduct similar attempts for various cross-sections thus enabling the construction of a three-dimensional form of the bubble, provided of course that the absence of the intervening gas ($N_H \approx 0$) holds.

The direct consequence of the local hot bubble is that, as seen in Figure 28, the solar system is located somewhat south of the median plane of the plasma region. This is a plausible explanation of the observed north-south asymmetry of the soft X-ray diffuse background.

Based on the local hot bubble model, the contribution from more distant hot regions can be evaluated in the following way. We assume that regions of a
temperature $T^*$ and an electron density $n_e^*$ are uniformly distributed with a filling factor $f$ among cool interstellar gas, outside the local hot bubble of a temperature $T$ and an electron density $n_e$ with an extent $R$. We may treat the distant hot plasmas approximately in the frame of Case B. The resultant soft X-ray flux is given by

$$I_g = \frac{1}{4\pi} \Lambda(T, E)n_e^2 R + \frac{f}{4\pi} \Lambda(T^*, E)n_e^* D(E)(1 - e^{-\sigma(E)N_H})$$  \hspace{1cm} (22)$$

where $D(E) = 1/\sigma(E)(n_H)$, the distance equal to one absorption optical depth. If we denote quantities in the L- and M-bands with subscripts L and M, respectively, the M/L ratio as a function of $N_H$ is expressed by

$$\frac{M}{L} = \frac{\Lambda_M}{\Lambda_L} \left[ 1 + f_{\xi_L} D_M R^{-1}(1 - e^{-\sigma_L M N_H}) \right]$$  \hspace{1cm} (22a)$$

where $\xi(E) = \Lambda(T^*, E)n_e^*/\Lambda(T, E)n_e^2$. Then, the expected amplitude of variation of the M/L ratio (ratio of the maximum to the minimum value of M/L) is approximately given by

$$r \equiv 1 + f_{\xi_M} D_M R^{-1}.$$

Since the M/L ratios observed, as shown in Figure 20, remain well within a factor of two ($r < 2$), excluding the Loop I and Loop II regions, it follows that

$$f < \frac{R}{D_M \xi_M} \sim \frac{\Lambda_M(T)n_e^2}{\Lambda_M(T^*)n_e^*^2} \times \frac{1}{20}$$  \hspace{1cm} (23)$$

since $D_M = (1-3)$ kpc for the range 0.5–0.8 keV and $R$ is estimated to be of the order of 100 pc in the next section. Hence, the regions similar in temperature and electron density to the local hot bubble ($T = T^*$, $n_e^* = n_e$) would have a filling factor of less than 5% at least in the celestial area scanned by Hayakawa et al. and within several kpc. In addition, the above relation also indicates that the $f$-value accommodated within the uncertainty of the M/L constancy quickly increases for smaller $n_e^*$ or a lower temperature than $10^6$ K.

8.3.1. Local Hot Bubble Model and the Global Features

In the context of the local hot bubble hypothesis, the global features of the soft X-ray brightness distribution may be further examined. In the available $N_H$-maps (e.g. Heiles and Jenkins, 1976; Kraushaar, 1977), one notices two wide regions of pronounced deficiency in neutral hydrogen: one in the northern hemisphere roughly covering the region $l \equiv 100^\circ - 200^\circ$, $b \equiv 45^\circ - 90^\circ$, and the other in the southern hemisphere covering $l \equiv 210^\circ - 330^\circ$, $b \equiv -45^\circ - 80^\circ$. Both regions are also bright in soft X-rays, which again points to a correlation between large-scale patterns in $N_H$ and the soft X-ray brightness. It is interesting to note that these two regions are roughly opposite to each other with respect to the Sun.

Equally striking is the geometrical relation of these two regions with Loop I and Loop II. Namely, the vector pointing at the approximate center of the northern
HI-deficient region is about 180° in longitude apart and approximately perpendicular to the vector pointing at the center of Loop I (see Table IV). The same situation exists between the southern HI-deficient region and Loop II.

This relation could be qualitatively interpreted in two different ways. One possibility (1) is that the hot bubble expanded, for some reason, along a preferential axis which is inclined by 60°–70° to the galactic plane, thereby resulting in more X-ray emission in these directions. A tilted gas disk like the one proposed by Fejes and Wesselius (1973) could be either the cause or the result of the directed expansion. In this case, the directional relation with the two radio loops is just by chance. Another possibility (2) is to consider that the hot bubble after it had been formed, interacted with the expanding shell of Loop I from one direction and with the Loop II shell from another direction. The expanding neutral shells of Loop I and Loop II will result in compression of the local hot bubble in the directions towards the Loops, thus reducing the X-ray intensity in the L-band in these directions. Hayakawa et al. suggest that the shape of the contour of the polar diagram in Figure 28 may indicate an interaction of this kind between Loop I and the local hot bubble.

At present, evidence which support such physical relationships as discussed above is still meagre, nevertheless, the geometrical correlation between neutral hydrogen, radio loops and soft X-rays, do not seem to be merely fortuitous.

9. Properties of the X-Ray Emitting Region

The current results reviewed in the preceding sections provide evidence that the soft X-ray diffuse background originates for the largest part from hot plasma. Discovery of O vi absorption lines was a timely evidence that indeed hot plasma with temperatures in excess of $3 \times 10^5$ K does exist in interstellar space, although the origin of O vi is still somewhat controversial. The important question arises then whether or not the same hot plasma is responsible for both the O vi absorption and the soft X-ray diffuse background.

In a plasma region the density of O vi ions is given by

$$n(O\text{ vi}) = \frac{n(O\text{ vi})}{n(O)} \frac{n(H)}{n(H)} \frac{n_e}{n_e}.$$ (24)

The ionization fraction $n(O\text{ vi})/n(O)$ calculated by Shapiro and Moore (1976) is given in Table V (Section 7.1), cosmical abundance of oxygen $n(O)/n(H) = 6.8 \times 10^{-4}$ and $n_e/n_H \approx 1.2$. As given in Equation (14) the mean density of O vi averaged for a number of observed stars is

$$\langle n(O\text{ vi}) \rangle \approx 1.7 \times 10^{-8} \text{ cm}^{-3},$$

although the variance is quite large.

Shapiro and Field (1976) have taken up this problem and investigated the consequences of such a hot component in the interstellar medium. Their analysis corresponds to our Case B. For the volume emissivity of soft X-rays in the range
0.18–0.28 keV, Shapiro and Field adopted the value from Silk (1973),

$$\Lambda(T, E) \langle n_e^2 \rangle \approx 7.5 \times 10^{-28} \text{ erg cm}^{-3} \text{ s}^{-1}.$$  

This approximately corresponds to the volume emissivity derived for a high flux region (north pole) (see 5.2), assuming $[\sigma(n_H)]^{-1} = 200 \text{ pc}$. Should a single plasma component be responsible for both the O VI absorption and the soft X-ray emission, the electron density $n_e$ and the filling factor $f$ are uniquely determined and can be calculated from these equations, where the filling factor $f(= \langle n_e \rangle^2 / \langle n_e^2 \rangle)$ equals the fraction of segments occupied by hot plasma regions along the line of sight. The resultant pressure $p/k = 2n_e T$ of the hot region is shown to follow the thick line in Figure 29 as a function of plasma temperature.

For a physically allowed range of $f(<1)$, the minimum pressure is reached at $T \approx 10^{6.1} \text{ K}$ in excess of $10^{4.2} \text{ cm}^{-3} \text{ K}$. This pressure is an order of magnitude larger than the currently accepted value of interstellar pressure $p/k \approx 10^{3.3} \text{ cm}^{-3} \text{ K}$ (Field, 

![Figure 29](image)

Fig. 29. (a) Pressure which satisfies the requirement that interstellar gas in ionization equilibrium at temperature $T$ explain both the soft X-ray flux and the O VI column density. (b) Pressure required to produce the soft X-ray flux with $f = 1$. (c) Same as (b), but with $f = 0.01$. (d) Pressure required to produce the O VI column density with $f = 1$. (e) Same as (d), but with $f = 0.01$. (f) Previously estimated interstellar pressure. Region below either curve (b) or (d) is unphysical since $f > 1$ (from Shapiro and Field, 1976).
1975). For a smaller filling factor, a larger electron density is required and which consequently results in a higher pressure.

Unless the nominal interstellar pressure is largely underestimated, which is according to Shapiro and Field still possible, such a hot region can not reach pressure equilibrium with the surrounding interstellar gas, since radiative cooling is not fast enough. Thus, Shapiro and Field conclude that the hot gas will continue to expand and eventually stream outside the gas disc. The gas which is gravity-bound will be brought back towards the galactic plane, which will be observed as negative-high-velocity clouds. According to the authors, this ‘galactic fountain’ model can explain the speed and the flux of the high-velocity clouds observed (Oort, 1970).

They also considered a time-dependent model in which the gas is allowed to cool from $10^6$ K to $10^4$ K. The result is essentially the same as the previous one with a temperature $T \approx 10^{5.8}$ K and the overpressure difficulty is even more severe.

Hayakawa et al. (1976b) and Burstein et al. (1976) investigated the implication of their data on soft X-rays under the restriction that the properties of the hot region do not conflict with the O vi result. It is shown in what follows that the overpressure problem does remain whatever plausible model for the spatial distribution of the X-ray emitting plasma is assumed. According to Hayakawa et al., the observed constancy of $M/L$ contradicts the spatial distribution for Case B but is rather in agreement with the local hot bubble model (Case A, $N_{hi} = 0$). The emission measure is consequently determined as

$$n_e R \equiv (0.6-1.2) \times 10^{-2} \, \text{cm}^{-6} \, \text{pc} \quad \text{for cosmical abundance (CA)}$$

or

$$(1.6-3.2) \times 10^{-2} \, \text{cm}^{-6} \, \text{pc} \quad \text{for partial depletion (PD)}$$

where depletion factors for the latter (PD) case are as mentioned before in Section 8.3. The smaller value applies for the region from the plane ($l \equiv 150^\circ$) to the south pole and the larger value corresponds to the north high latitude region $b \equiv 45^\circ-90^\circ$, $l \equiv 150^\circ$, respectively.

The contribution of the hot bubble to the O vi column density is estimated from Equation (24) by employing the temperature determined from the X-ray spectrum, and amounts to:

$$N(\text{O vi}) = 5.5 \times 10^{12} \, n_e R \, \text{cm}^{-3} \, \text{pc} \quad \text{for} \quad kT = 0.13 \, \text{keV} \quad (\text{CA})$$

or

$$\equiv 8.2 \times 10^{12} \, n_e R \, \text{cm}^{-3} \, \text{pc} \quad \text{for} \quad kT = 0.10 \, \text{keV} \quad (\text{PD}),$$

where oxygen is assumed to be undepleted.

In order not to contradict the observed O vi data for $T_m \approx 10^6$ K, Equation (26) may not exceed an upper limit. Placing the upper limit at $10^{13}$ O vi atoms cm$^{-2}$ for the local hot bubble (see Figure 17), its extent at low latitude may not be greater than 100 pc (for PD) or 550 pc (for CA) from Equation (25) and (26). The extent towards the northern high latitude would be about doubled.
The minimum electron density required is $3.3 \times 10^{-3}$ ($kT = 0.13$ keV) to $1.3 \times 10^{-2}$ cm$^{-3}$ ($kT = 0.10$ keV), resulting in a minimum pressure $p/k$ of $(1-3) \times 10^4$ cm$^{-3}$ K.

The lower value of the pressure is realized only if the local hot bubble extends about 1 kpc above the galactic plane, which seems rather unrealistic. If the height of the hot region above the plane is assumed to be comparable to the thickness of the gas disc, say 100 pc, the electron density is estimated to be

$$n_e \approx 1.1 \times 10^{-2} \text{ cm}^{-3} \quad \text{for CA}$$

or

$$1.8 \times 10^{-2} \text{ cm}^{-3} \quad \text{for PD}$$

(27)

The pressure increases accordingly to $p/k = (3-4) \times 10^4$ cm$^{-3}$ K for either model of the abundances.

As a matter of fact, this conclusion remains valid without the O vi restriction, since $N$(O vi) from the hot bubble is now appreciably smaller than the limit of $10^{13}$ atoms cm$^{-2}$. Moreover, for those O vi absorption lines with maximum temperature $T_{\text{max}} < 10^6$ K, the absorption profile due to the hot bubble would only contribute to the high velocity wing which may hardly be distinguishable (York, 1974).

The dispersion measures of pulsars seem to give consistently larger electron densities than those derived above, typically $\langle n_e \rangle = 0.04$ cm$^{-3}$ (Groth, 1975). If this value would apply to the hot plasma concerned, it leads to a still higher pressure. However, in view of large uncertainties in the determination of pulsar distances, the pulsar dispersions do not seem to restrict a smaller electron density in particular in the local space.

Levine et al. (1976b), based on Case B, derived an emission measure for soft X-rays in the region of mid- to low intensity in the southern hemisphere,

$$\text{emission measure} = (1.6^{+1.5}_{-0.8}) \text{ cm}^{-6} \text{ pc},$$

assuming cosmical abundances, and a rms electron density $n_e = (7 \pm 3) \times 10^{-3}$ cm$^{-3}$ for $\langle n_{\text{H}} \rangle = 0.2$ atoms cm$^{-3}$. They estimated the temperature to be $(4-8) \times 10^5$ K. If we adopt the medium value of $6 \times 10^5$ K and put the restriction that $\langle n$(O vi)$\rangle$ expected from the X-ray emitting plasma does not exceed $1.7 \times 10^{-8}$ cm$^{-3}$, it follows that the filling factor $f$ is less than 3% and the pressure $p/k \geq 5 \times 10^4$ cm$^{-3}$ K.

Burstein et al. (1976) also reached a similar conclusion from a detailed band fraction analysis based on either Case A or Case B. As mentioned in Section 8, the result of Burstein et al. requires, in the part of the sky they observed, at least two temperature components. They examine the pressure problem for the lower and the higher temperature component separately by assigning an emission measure $n_e^2 R$ (Case A) or its equivalence $\langle n_e^2 \rangle / \langle n_{\text{H}} \rangle \sigma$ (Case B) to the respective components, which is a function of the temperature assumed as illustrated in Figure 30. It is pointed out that in this way the severe overpressure difficulty Shapiro and Field (1976) encountered below $10^6$ K (see Figure 29) can be substantially eased. Since the X-ray
Fig. 30. (a) Curves of the emission measure as a function of temperature necessary to produce a normalized count rate over a defined soft X-ray passband (Burstein et al., 1976). Calculations have been made for Case A (Model I) and Case B in the limit of large $N_{H}$ (Model III). Normal abundances have been assumed. (b) Same as (a) but for depleted abundances.
emissivity in the L-band is sharply reduced with lowering the temperature below $6 \times 10^5$ K, a very large $n_e$ and hence a large pressure was necessary to account for the measured soft X-ray flux in the model of a single temperature component. Whereas if a second component of a higher temperature is present, it will account for a large part of the L-band emission. The pressure vs. temperature diagram for the lower temperature component Burstein et al. derived is shown in Figure 31.

O vi restrictions are taken into account by these authors in such a way that $N(O\text{ vi}) < 10^{13}$ atoms cm$^{-2}$ for Case A and $n(O\text{ vi}) < 1.7 \times 10^{-8}$ cm$^{-3}$ for Case B for the soft X-ray emitting plasma. Note that the pressure given in the diagram is the lower limit for the respective models at a given temperature. For Case B the pressure $p/k$ is nowhere below $10^4$ cm$^{-3}$ K. Whereas, $p/k$ for Case A, is read substantially lower than $10^4$ cm$^{-3}$ K around $10^6$ K. However, this only holds, as shown in the lower diagram, provided that the radius of the hot region is far greater than 100 pc, which seems unrealistic.

Thus a pressure of the X-ray emitting region exceeding $10^4$ cm$^{-3}$ K seems to be an inevitable consequence of the strong soft X-ray luminosity observed, independent of whether they are local or of galactic scale.

Fig. 31a. The minimum pressure and the maximum extent of the hypothetical local hot region in Case A, assuming $N_H = 0$ (Burstein et al., 1976).
Fig. 31b. The minimum pressure and the maximum filling factor for Case B (dispersed hot gas in the cool interstellar medium) in the limit of large $N_H$ (Burstein et al., 1976). Full lines are derived for cosmical abundances and the dashed lines assume depleted abundances as observed for ζ Oph (Morton, 1975, see Figure 22).

One cannot be free from the conclusion at present that the X-ray emitting plasma is not in pressure equilibrium such as to permit a steady state picture but is expanding.

Burstein et al. mention an interesting attempt of Lenz (1976) whereby a maximum temperature $T_m$ derived from the FWHM of a blended O vi absorption line profile varies little from $2.75 \times 10^5$ to $5 \times 10^5$ K even for a largely varied temperature distribution of the form $T^\alpha$ in the range of $\alpha = -5$ to $+1$. It may be indeed so that the absorption lines indicating a maximum temperature exceeding $10^6$ K are a blend of plural components with different Doppler shifts. A tendency is noticeable in Figure 17 that those stars showing $T_m > 10^6$ K are on the average more distant and, consequently, their line of sight has more chance to intersect different hot regions, although selection effects cannot be ruled out.

A similar result is obtained by the following consideration. Given a column density of O vi at a certain temperature towards a star, a lower limit of the emission measure
to the star can be estimated from Equation (24) and the ionization fraction given in Table VI, by putting the filling factor equal to unity. If the temperature derived from the width of the O vi absorption lines is representative for the actual temperature of the intervening plasma, those stars for which \( T_m > 10^6 \) K can be employed for comparison with the observed soft X-rays in the same temperature regime. Taking the ionization fraction at \( 10^6 \) K, it follows that

\[
\langle n_e^2 \rangle R_* \geq \left( \frac{N(O \text{ vi})}{10^{13}} \right)^2 R_*^{-1},
\]

where \( R_* \) denotes the distance to the star for which the measured O vi column density is \( N(O \text{ vi}) \). From the O vi results shown in Figure 17, the majority of stars with \( T_m > 10^6 \) K yields a lower limit of the emission measure which is larger, for some stars more than an order of magnitude, than the range determined from the soft X-ray data (see (25)).

This contradicts the soft X-ray results at least in the M-band, since most of the O vi-measured stars are within 1 kpc, appreciably smaller than one optical depth. This seems to imply that the actual plasma temperature is considerably lower than that the line widths indicate at least for those with \( T_m > 10^6 \) K.

Thus, it is rather unlikely that the same hot plasma regions are responsible for both the O vi absorption and the soft X-ray emission which we observe.

As estimated in Section 8, hot bubbles with a temperature \( \sim 10^6 \) K such as the local one do not seem to be numerous in the galactic disc. The constant M/L ratio observed by Hayakawa et al. (1976b) over a wide latitude range of the sky limits the population of such high temperature bubbles. However, those bubbles with temperatures below \( 8 \times 10^5 \) K could be as abundant as to fill up 10% or more of the galactic disc without introducing a conflict with the observed constancy of the spectral shape.

In fact, the observed O vi absorption can be accounted for, if a plasma of temperature \((3-5) \times 10^5 \) K under pressure equilibrium with the surrounding interstellar matter fills up about 10% of the galactic disc. These considerations seem to be consistent with the fact that sharp absorption lines with \( T_m < 5 \times 10^5 \) K are frequently observed.

### 10. Summary

Summarizing the preceding discussions, the following picture emerges:

1. The available observational evidence suggests that an extended region surrounding the solar system is mostly filled with hot plasma at a temperature of the order of \( 10^6 \) K, which is consistent with a local ‘hot bubble’. This region could hardly be in pressure equilibrium with the surrounding cool interstellar matter.

   Except for several enhanced regions, a major fraction of the soft X-ray diffuse background is accounted for by the thermal emission from this region.

2. This hot region would be extending from the galactic plane to a larger height to the north than to the south. This explains the observed north-south asymmetry of the...
soft X-ray brightness. Similarly, its directional dependence in general may be interpreted in terms of the location of the solar system within the local hot bubble.

(3) Among several extended regions of enhancement, Loop I (North Polar Spur) is the most prominent one. Accumulating X-ray data support the hypothesis that Loop I is a giant supernova shell. Spectral analysis indicates the presence of strong oxygen lines in the M-band, which permits a fair estimate of the temperature at approximately $3 \times 10^6$ K.

Observed features of other enhancements in Gemini, Eridanus, Loop II and Lupus are also suggestive of a supernova origin. Thus, supernovae undoubtedly play an important role in the formation and heating of the X-ray emitting plasma in interstellar space.

(4) Hot regions with a temperature higher than $10^6$ K seem to be scarce at least within a few kpc from the Sun. Lower temperature regions between $10^6$ K and $3 \times 10^5$ K may be more abundant, these make the major contribution to the O vi absorption, but contribute only slightly to the soft X-rays observed in the L-band.

Our tentative conclusion is therefore that the plasma responsible for soft X-ray emission and that for O vi absorption cannot be one and the same component but belong to somewhat different temperature regimes.

Thus, the observation of soft X-rays is an indispensible mean for the investigation of the interstellar medium at the highest temperature phase in its hierarchy. Further progress in observation, with improvements in technology, will reveal details of the properties and dynamics of these high-temperature plasma regions. There are two obvious directions for the development in the near future. (1) spectroscopy which enables us to disentangle the problems of temperature, abundances of elements and fine spatial structures, and (2) the extension of observations towards the longer wavelength region, EUV, which is still almost unexplored.

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THE DIFFUSE SOFT X-RAY SKY