20. ABSORPTION AND PRODUCTION OF SOFT X-RAYS IN THE GALAXY

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Abstract. The column densities of interstellar hydrogen to X-ray sources derived from their spectra are compared with those obtained from 21 cm radio observations. Referring to several observed results on Cyg X-2, Cygnus Loop etc., the interpretation of the low energy cut-off of the spectrum in terms of the interstellar absorption is subject to ambiguities due to a modification of the emission spectrum by Compton scattering in the sources and the contribution of emission lines.

The result of soft X-ray sky surveys indicates that the diffuse component of soft X-rays consists of the extragalactic and the galactic components. The former has a hard component with a power law spectrum and a soft component which may be represented by an exponential spectrum. The galactic component is so soft that its spectrum may also be explained by thermal bremsstrahlung of temperature of about 0.1 keV. Its generation rate may account for the heating and ionization of interstellar matter. It is suggested that galactic diffuse soft X-rays are produced by active stars of a rather high number density.

1. Introduction

The observation of cosmic X-rays has been extended towards low energy to see the distances of X-ray sources through the modification of their spectra by interstellar absorption and the density of interstellar matter through the distribution of the diffuse component over the celestial sphere. However, results of soft X-ray observations thus far obtained are more complicated than one would have thought.

For some X-ray sources such as Cygnus Loop, the distances derived from the turn-over of their spectra seem to be significantly different from those obtained from the radio observations of the 21 cm line and other astronomical information. As for the diffuse component of soft X-rays, their intensity at low galactic latitudes is much stronger than that expected from the interstellar absorption of the extragalactic component, thus suggesting the contribution of the galactic component.

2. Interstellar Absorption and Scattering of X-Rays

The X-ray spectrum of a source is expressed by the product of the emission spectrum $Q(E)$ and the attenuation coefficient $A(E)$ as

$$J(E) = A(E)\,Q(E),\; A(E) = \exp[-N_H\sigma(E)], \tag{1}$$

where N_H is the column density of hydrogen atoms and $\sigma(E)$ is the effective attenuation cross section per hydrogen atom for X-rays of energy E.

In most works the cross section given by Brown and Gould (1970) is adopted. This is based on the photoelectric absorption by interstellar atoms and may be approximately expressed, below and above the oxygen K-edge, by

$$\sigma(E) = \begin{cases} 6.0 \times 10^{-20}(0.1\ \mathrm{keV}/E)^3\ \mathrm{cm}^2 & \text{for}\quad 0.1\ \mathrm{keV} \leqslant E \leqslant 0.53\ \mathrm{keV}, \\ 2.0 \times 10^{-22}(1\ \mathrm{keV}/E)^{2.5}\ \mathrm{cm}^2 & \text{for}\quad 0.53\ \mathrm{keV} \leqslant E \leqslant 10\ \mathrm{keV}, \end{cases} \tag{2}$$

Bradt and Giacconi (eds.), X- and Gamma-Ray Astronomy, 235–249.

It may be worth mentioning the role of dust grains. A considerable fraction of carbon, oxygen and heavier nonvolatile elements may form dust grains whose density is of the order of 10^{-12} cm^{-3}. For X-rays of energies higher than 1 keV the optical depth of a grain is so small that the interstellar absorption is independent of whether these heavy elements form grains or not. As energy decreases, however, the effective absorption coefficient may be reduced, since the optical depth of a single grain approaches unity, if the fraction of the elements forming grains is considerable. On account of that oxygen is mainly responsible for the photoelectric absorption at energies above 0.53 keV, the K-edge of oxygen, and that it is about 30 times more abundant than silicon, with which one of the major constituents of dust grain, SiO_2 is formed, the photoelectric absorption of dust grains is considered to be of minor importance, unless grains adsorb a great amount of H_2O.

Nevertheless, the effect of dust grains is not always negligible because they scatter soft X-rays. The half width of the scattering angle for a spherical grain of radius a in μ is as large as (Hayakawa, 1970)

$$\theta_s = 10(1\ \text{keV}/E)(0.1\ \mu/a)\ \text{arc min} \tag{3}$$

and the scattering coefficient at $\frac{1}{4}$ keV may be as large as $\frac{1}{4}$ of the photoelectric absorption coefficient predicted by (2). If, therefore, a compact source is measured with a good angular resolution, the attenuation effect for the source is greater than expected from the photoelectric absorption.

The effect of dust grains will be more clearly observed through time variations. Since photons scattered are considerably delayed, even if the scattered angle is very small, pulsations of short periods may be washed out by scattering (Slysh, 1969; Naranan and Shah, 1970). Such an effect could be observed for Cen X-3 and Cyg X-1 at about 0.8 keV and lower energies.

Since detailed properties of interstellar dust grains are not yet established, their effects as discussed above are not quantitatively predictable but will have to be revealed by future observations.

3. Distances of X-Ray Sources

The hydrogen column density to an X-ray source has been derived by assuming an emission spectrum

$$Q(E) \propto E^{-1} \exp(-E/kT) \tag{4a}$$

or

$$Q(E) \propto E^{-\alpha}. \tag{4b}$$

It should be noted that the value of N_H thus derived, which is denoted as N_{Hx}, depends rather sensitively on the shape of the spectrum assumed. The expression (4a) implies that X-rays are emitted by thermal bremsstrahlung. Some authors use a more exact expression applicable to thin plasmas

$$Q(E) \propto E^{-1} \exp(-E/2\,kT)\, K_0(E/2\,kT), \tag{4c}$$

$$K_0(x) \simeq \begin{cases} \ln(2/x) - 0.577 & \text{for} \quad x \ll 1 \\ (\pi/2x)^{1/2} \exp(-x) & \text{for} \quad x \gg 1, \end{cases}$$

in place of (4a). This gives a larger value of N_{Hx} if the turn-over energy is much smaller than kT. For optically thick sources such as Sco X-1 the emission spectrum has a complicated shape and may turn over without the interstellar absorption.

The value of N_{Hx} for Sco X-1 obtained with (4a) is $(30–40) \times 10^{20}$ cm^{-2} (Grader *et al.*, 1970a; Burginyon *et al.*, 1970), whereas the 21 cm emission line intensity gives about 10×10^{20} cm^{-2} (Goldstein and MacDonald, 1969). The difference has been interpreted as due to circumstellar cold matter. It is not easy to find such thick cold matter that is left unionized under a high X-ray flux, that is held against a high radiation pressure and that does not produce absorption lines. Since the turn-over point may change from one experiment to the other, it is likely that the spectrum at low energies is partly modified by Compton scattering in the X-ray emitting region, and the modification changes with the optical depth for the Compton scattering.

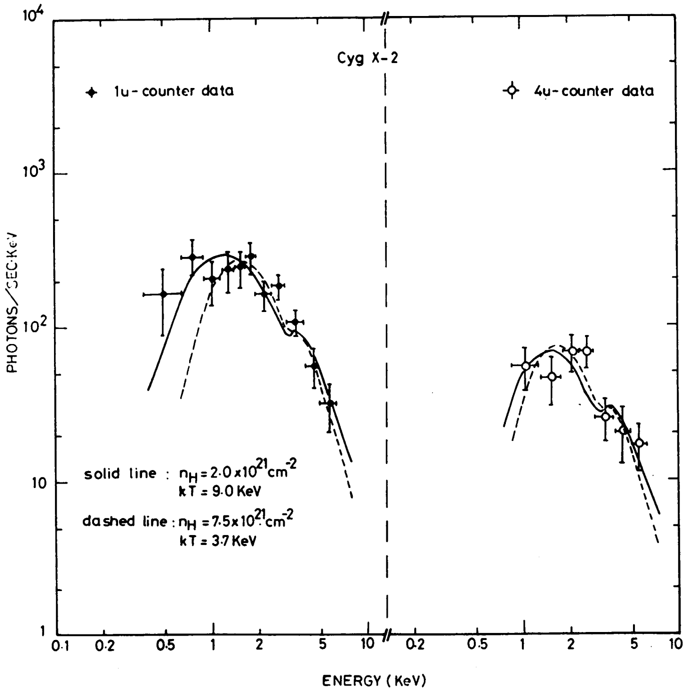

Fig. 1. Energy spectrum of Cyg X-2 (Bleeker *et al.*, 1972). The pulse height distributions obtained with two kinds of counters of different window thicknesses are compared with those expected from the thermal bremsstrahlung spectra modified by the interstellar absorption. The solid lines represent the best fit to all experimental points, whereas the dashed lines fit to the points for $E \geqslant 0.9$ keV.

The variation of the spectrum in the low energy part may be of experimental origin rather than of genuine variations in the source. The spectrum of Cyg X-2 provides an instructive example. An observation with counters of poor efficiency at low energies gave N_{Hx} of about 200×10^{20} cm^{-2} although the quoted errors were rather large (Gorenstein *et al.*, 1967), whereas another with high efficiency resulted in a value as small as 20×10^{20} cm^{-2} (Hayakawa *et al.*, 1971). It has been demonstrated by Bleeker *et al.* (1972) that the value of N_{Hx} depends on the lower cut-off energy of the spectrum using a single observation with high efficiency counters. $N_{Hx} \simeq 75 \times 10^{20}$ cm^{-2} is derived on the basis of the spectrum for $E \geqslant 0.9$ keV, whereas $N_{Hx} \simeq 20 \times 10^{20}$ cm^{-2} if lower energy data ($E \geqslant 0.16$ keV) are included, as shown in Figure 1. A reason for giving such considerably different values is due, at least in part, to the flatness of the spectrum around 1 keV. It is likely that the emission spectrum cannot be represented by any one of the simple spectra given in (4a–c).

Another example is provided by Cygnus Loop. Grader *et al.* (1970b) obtained $N_{Hx} = 2.5 \times 10^{20}$ cm^{-2}, assuming $\alpha = 3.2 \pm 0.3$ for (4b) or $kT = 0.4$ keV for (4c). Gorenstein *et al.* (1971) also gave a small value, $N_{Hx} = 2.6 \times 10^{20}$ cm^{-2}, assuming $kT = 0.37$ keV for (4a) plus a contribution of a 0.65 keV line of O VIII. The average hydrogen density over the distance to the Cygnus Loop would then be as small as 0.1 cm^{-3} if 770 pc is adopted as the distance of Cygnus Loop. The spectrum observed by Bleeker *et al.* (1972) may again be explained by a small value of N_{Hx} with a weak contribution of emission lines, but may also be represented only by a continuum with a greater value of N_{Hx}, $(5–7) \times 10^{20}$ cm^{-2}. Even if such a large value of N_{Hx} is adopted, the average hydrogen density of 0.2–0.3 cm^{-3} over the distance of 770 pc is smaller than that currently adopted for the density in the direction of Cygnus Loop (Daltabuit, 1970).

The third example is Cyg X-1. Gursky *et al.* (1971) obtained $N_{Hx} = (16 \pm 4) \times \times 10^{20}$ cm^{-2} assuming a power spectrum of $E^{-1.7 \pm 0.1}$, whereas a larger value of N_{Hx} is not ruled out for a steeper spectrum $E^{-2.6 \pm 0.3}$ as observed by Bleach *et al.* (1972). Incidentally, the distance of its possible optical counter part, HD 226868, is about 2 kpc, corresponding to $N_{Hx} \simeq 40 \times 10^{20}$ cm^{-2}.

It is unfortunate that both the interstellar absorption and the Compton scattering in sources modify the spectrum at energies slightly below 1 keV for sources at distances of several hundreds of parsec and the optical thickness of ten or greater. The contribution of emission lines gives rise to further complexity. The separation of the absorption effect from the emission spectrum will require more experimental effort.

Keeping these difficulties in mind, the values of N_{Hx} obtained for X-ray sources are compared with N_H (21 cm) from radio observations in Figure 2, extending a compilation by Ilovaisky (1971). Only for SNR of strong radio emission the absorption line of 21 cm is observed, and the hydrogen column density obtained therefrom is denoted as N_{Hab}. For other sources comparison can be made only with the emission line intensity in the direction of each X-ray source, and the hydrogen column density for the emission line is denoted as N_{Hem}. The values of N_{Hab} and N_{Hem} derived from radio observations depend on the spin temperature, so that the reliability of these values becomes poorer as the galactic latitude decreases. For $|b| \gtrsim 10°$ the optical depth at 21 cm becomes so small that $N_{\mathrm{H_{em}}}$ depends only weakly on the spin temperature. Moreover, X-ray sources at such latitudes are likely to lie towards the edge of the galactic disk, so that $N_{\mathrm{H_{em}}}$ may be close to the hydrogen column densities to the sources. Hence the comparison of $N_{\mathrm{H_x}}$ with $N_{\mathrm{H_{em}}}$ is of greater significance for sources with $|b| \gtrsim 10°$.

The relation between $N_{\mathrm{H_x}}$ and N_{H} (21 cm), shown in Figure 2, should be considered as illustrative, on account of the discussions given above. Most values of $N_{\mathrm{H_x}}$ are taken from Hill *et al.* (1972) and are subject to considerable statistical errors and to dependences on the spectral shape assumed. The values of $N_{\mathrm{H_{em}}}$ are based on a compilation by Daltabuit (1970), in which different 21 cm observations do not always give mutually consistent results, in particular for $b=0°$.

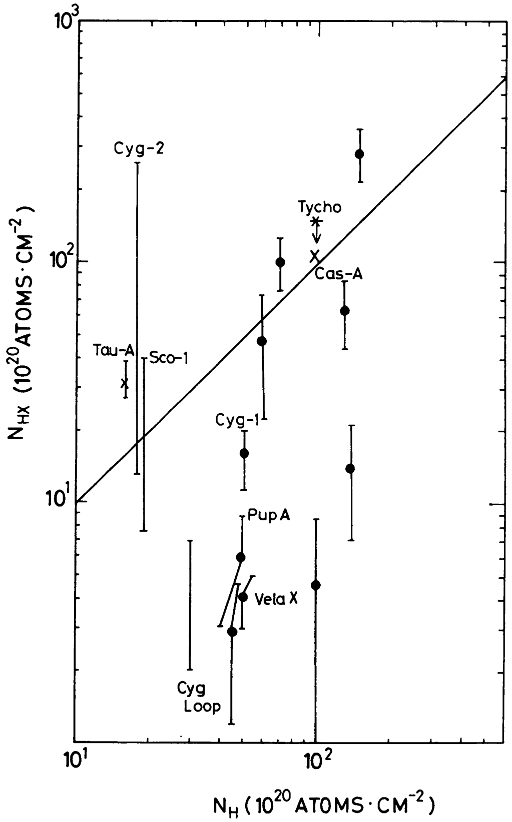

Fig. 2. The hydrogen column densities obtained from X-ray spectra (N_{Hx}) and 21 cm radio intensities (N_{H}). In the latter the crosses (×) represent N_{Hab}, whereas others represent N_{Hem}. The uncertainties in the values of N_{Hx} due to fitting of the observed spectra to expressions (1) with (4) are indicated by vertical bars with solid circles. For Sco X-1, Cyg X-2 and the Cygnus Loop the experimental values are so widely scattered that the ranges of N_{Hx} are indicated by vertical bars. References to the values of N_{Hx} for the named sources can be found in the text, whereas the unnamed ones are based on Hill *et al.* (1972).

Within the uncertainties in the numerical values of N_H, a general trend indicates $N_{Hx} \lesssim N_{Hem}$. For Sco X-1 and Cyg X-3 there hold $N_{Hx} > N_{Hem}$, thus suggesting the presence of circumstellar matter or emission spectra with maxima at corresponding energies.

There are several sources for which $N_{Hx} < < N_{Hem}$. For SNR's, Cygnus Loop, Vela X and Pup A, the distances are estimated from the expansion velocities and the angular diameters (Milne, 1970). In all three cases the hydrogen densities averaged over the distances are as small as 0.2–0.3 cm^{-3}, which is compared with about 0.7 cm^{-3} obtained from 21 cm observations. If, however, these SNR's are surrounded by H II regions with radii depending on their ages, as in the case of the Gum nebula around Vela X (Brandt *et al.*, 1971), the hydrogen density in the H I region estimated from N_{Hx} may have to be increased by a factor of two or so.

Other sources with small N_{Hx} are not fully studied yet. Some of them may be variables, since those observed by one flight are not detected by others.

4. Distribution of the Diffuse Component

At energies greater than 1.5 keV the diffuse component is isotropic within a few per cent (Cooke and Pounds, 1971) and consequently has been regarded as extragalactic origin. Anisotropy should be expected at lower energies, since extragalactic X-rays are subject to interstellar absorption. It has been found, however, that the intensity of diffuse X-rays of energies around 0.25 keV decreases towards the low galactic latitude more slowly than expected from the interstellar absorption and remains to be considerable at the galactic equator. This is hardly understandable if the diffuse component is exclusively of extragalactic origin and suggests the existence of the galactic component in the energy range below 1 keV.

Since only a limited sky region has been scanned by a single rocket observation, and since different observations have not always given the same absolute intensity, it is not easy to construct the celestial distribution of the soft X-ray intensity. This has been attempted by Kato (1972), normalizing the intensities in the direction of the lowest hydrogen column density and referring to five observations with high counter efficiencies at the carbon window. A survey over a wide sky region has been made by the Leiden-Nagoya collaboration, called LEINAX (Bleeker *et al.*, 1972). These two results are in essential agreement with eath other. Here the LEINAX result is presented, in view of that the same counters were used for scanning and the statistical accuracy is better than in earlier observations.

The celestial distributions in the pulse height ranges 0.37–0.65 keV and 0.65–0.90 keV are shown in Figure 3a and Figure 3b, respectively. Since the counts obtained with the 1μ counters are averaged over the spin angle of 10°, the spatial resolution is 25° × 13° (FWHM) with the greater angular extension perpendicular to the scan path. In the range 0.37–0.65 keV the counter efficiency has a dip, so that incident X-rays in the energy range 0.23–0.8 keV contribute to this pulse height range. Because of the softness of the X-ray spectrum the distrubition in Figure 3a is dictated by that in the

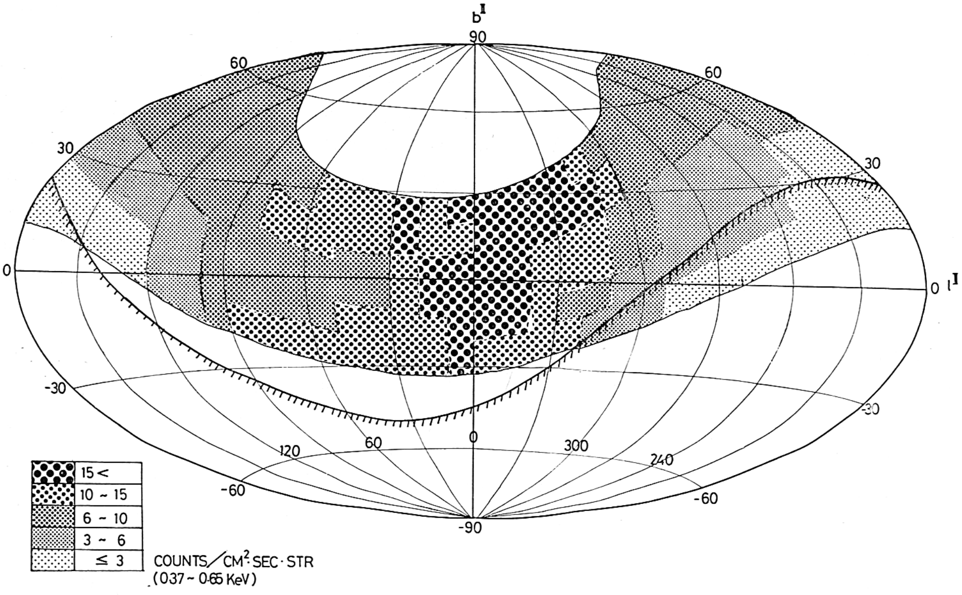

Fig. 3a.

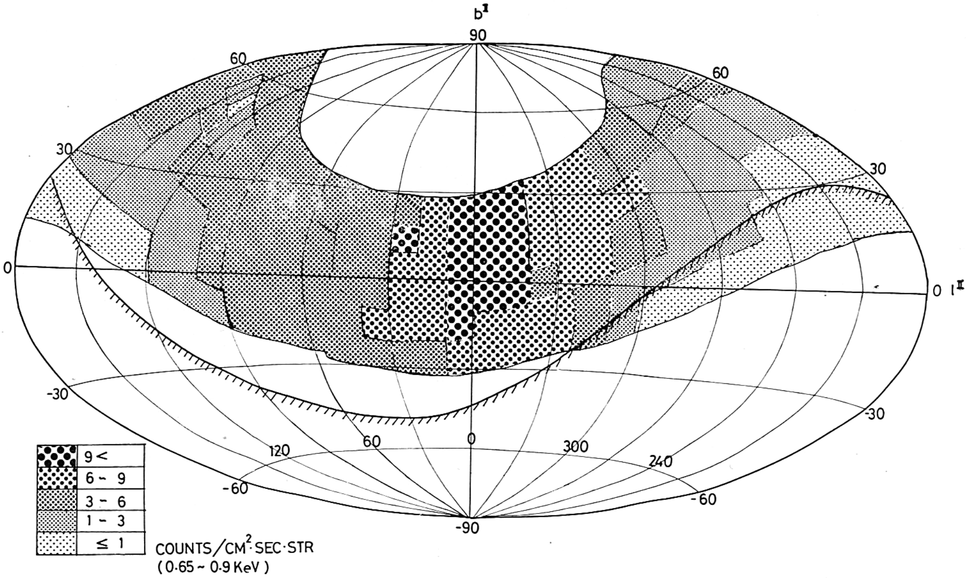

Fig. 3b.

Figs. 3a–b. Celestial distributions of the soft X-ray intensity. (a) $E = 0.37–0.65$ keV, (b) $E = 0.65–0.90$ keV. The position at which the counting rate is given corresponds to the direction of the counter axis.

X-ray energy range 0.23–0.28 keV. In the pulse height range 0.65–0.90 keV, the main contribution comes from X-rays of energies around 0.8 keV.

The distributions in these two ranges are apparently similar to each other. The intensity is strong towards the galactic center and gradually decreases as one recedes from the center. The strong intensity in the galactic center region is due partly to the contribution of X-ray sources; only the Cygnus Loop is avoided in mapping the distribution. In a still lower energy range the enhancement in the center region almost disappears, although in this range spurious counts due to ultraviolet radiation and the noise arising from the electrostatic field for electron rejection have to be subtracted.

In the anticenter region the intensity gradually increases with the galactic latitude. This fact has been attributed by Kato (1972) and other authors of earlier observations to the absorption of extragalactic X-rays. On the other hand, Gorenstein and Tucker (1972) have assumed that the majority of soft X-rays ($E \lesssim 0.25$ keV) is due to the galactic component even at the highest latitude, based on the absence of the correlation with the hydrogen column density in the Virgo region and referring to the absence of absorption by Small Magellanic Cloud (Bunner *et al.*, 1971b). It should, however, be remarked that the comparison of the intensities in two selected regions, as attempted by Gorenstein and Tucker (1972), may not always be an acceptable procedure, in view of irregularities in the intensity distribution.

The correlation between the X-ray intensity and the hydrogen column density is shown in Figure 4 in the anticenter region ($90° \leqslant l \leqslant 270°$), in which irregularities seem to be less important. The N_H dependence observed is in good agreement with that expected from the absorption of the extragalactic component by homogeneous interstellar matter.

The separation between the extragalactic and the galactic components depends also on their energy spectra. The spectrum of the former has been represented by a power law, $E^{-1.4}$, between 1 and 10 keV (Bunner *et al.*, 1971a). If this is extrapolated to lower energy, there remains an excess intensity below 1 keV. At low latitudes the excess soft X-rays cannot be due to the extragalactic component, since its contribution, if any, is negligible because of the interstellar absorption. Assuming that the excess part observed in the celestial region, $90° \lesssim l \lesssim 180°$ and $-10° \lesssim b \lesssim 30°$, in which $N_H \gtrsim 30 \times 10^{20}$ cm^{-2}, is due entirely to the galactic component, we derive the generation rate of galactic X-rays.

For the sake of simplicity we assume uniform slab models for the distributions of X-ray emissivity and interstellar matter, the half thicknesses of the slabs being β_x and β_H, respectively. The intensity at latitude b is related to the X-ray emissivity $g(E)$ as

$$j_g(E, b) = \frac{1}{4\pi} g(E) \left[\frac{1 - \exp(-\sigma(E) N_H)}{\sigma(E) n_H} + \frac{\beta_x - \beta_H}{\sin b} e^{-\sigma(E) N_H} \right], \qquad (5)$$

where $\beta_x \geqslant \beta_H$ is assumed. In the low latitude region, $\exp(-\sigma N_H)$ is negligibly small

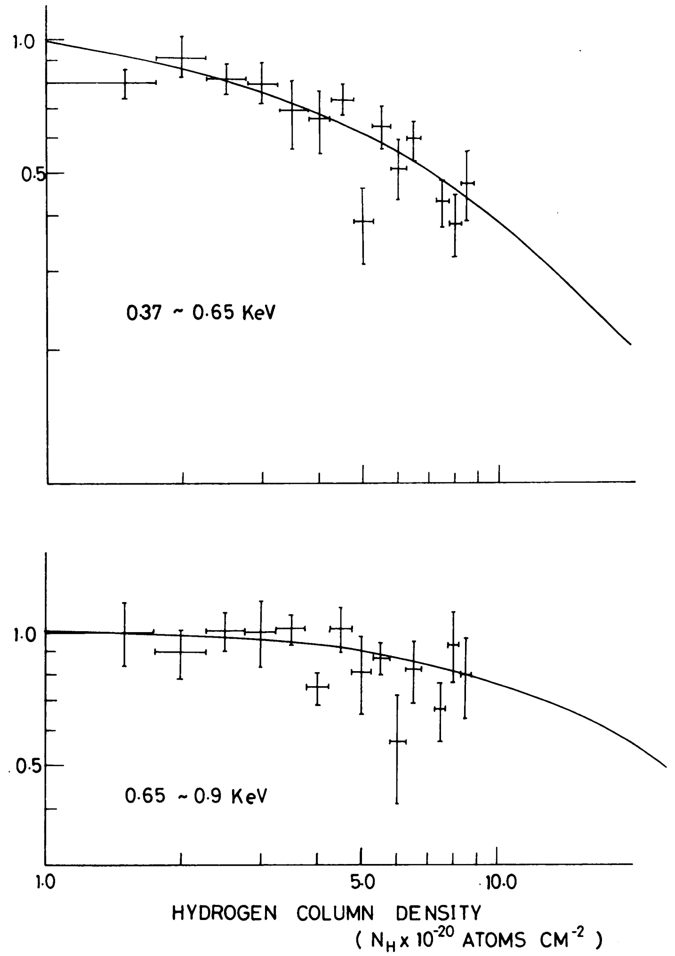

Fig. 4. The soft X-ray intensities versus the hydrogen column density. The intensities are adopted from the observations in the anticenter side and the curves represent the absorption of extragalactic X-rays expected in the respective energy ranges.

in the energy range of interest. Hence the X-ray emissivity is obtained as

$$g(E) \simeq g_0 n_{\mathrm{H}} E^{-1} \exp(-E/kT) \text{ photons cm}^{-3}\text{ s}^{-1}\text{ keV}^{-1}, \tag{6}$$

with $g_0 = 3 \times 10^{-17}$ photons s^{-1}, $kT = 0.1$ keV.

This gives the energy generation rate

$$G = \int Eg(E)\,\mathrm{d}E \simeq 5 \times 10^{-27}\, n_{\mathrm{H}} \text{ erg cm}^{-3}\text{ s}^{-1}. \tag{7}$$

In the high latitude region the contribution of the galactic component can be evaluated from the expression (5) with (6), provided that the value of β_x is known.

However, the contribution of the term containing β_x can be distinguished from that of the extragalactic component only through its cosec$b$ dependence. The counting rates around $l = 120°$, $b = 25°$ and around $l = 240°$, $b = 55°$ are nearly the same, and the values of N_H in these regions are about equal, 5×10^{20} cm^{-2}. This results in an upper limit of $(\beta_x/\beta_H) - 1 \lesssim 0.2$, provided that the diffuse soft X-rays are exclusively of the galactic origin.

Since the contribution of the second term in (5) seems to be of secondary importance, we neglect this term for the time being. In the low latitude region a superposition of the galactic component with emissivity given in (6) and the extragalactic component of the $E^{-1.4}$ spectrum modified by the interstellar absorption reproduced the oberved spectrum, as shown in Figure 5. A superposed spectrum in the high latitude region, $90° \lesssim l \lesssim 270°$ and $b \gtrsim 40°$, in which $N_H \lesssim 5 \times 10^{20}$ cm^{-2}, is compared with the observed spectrum. The latter is found to be about twice greater than the

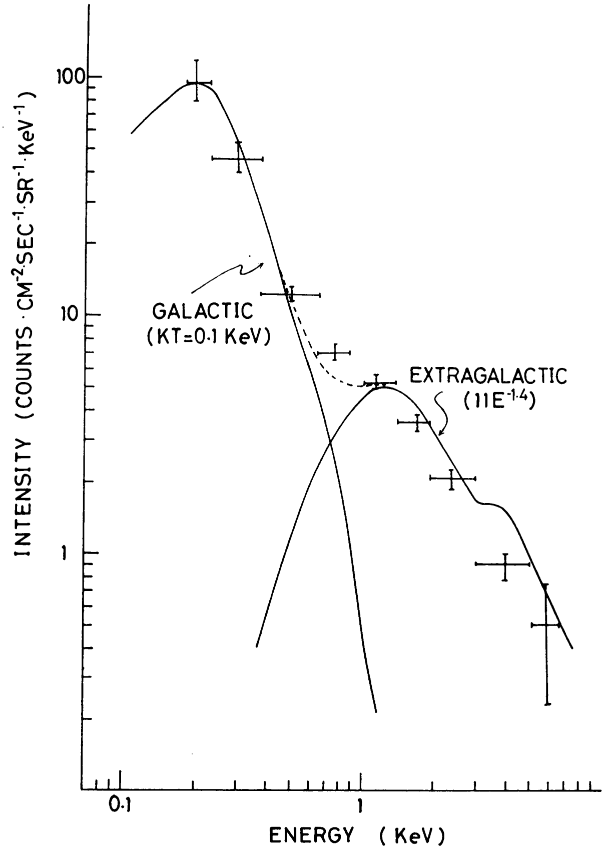

Fig. 5. X-ray spectrum in the low latitude region. The solid curves represent the pulse height spectra of the galactic and the extragalactic components, taking into account the interstellar absorption for $\langle N_H \rangle = 30 \times 10^{20}$ cm^{-2}, the counter efficiency and the energy resolution. The dashed curve represents their sum. The observed points are based on the results obtained with the 1 μ LEINAX counters.

former in the pulse height range below 0.37 keV. The excess is accounted for in terms of the exponential spectrum of $kT=0.1$ keV modified by the absorption of $N_H=3\times10^{20}$ cm^{-2}. A superposition of the galactic component and the extragalactic component, the latter consisting of the power law and the exponential law spectra, is compared with the observed one in Figure 6.

Thus the general behaviour of the diffuse soft X-rays may be understood as a mixture of the galactic and the extragalactic components. However, the conclusion will be reserved for future investigation, since the LEINAX data are contaminated with ultraviolet radiation and the angular resolution is not good enough for unambiguous separation between the N_H and the b dependences.

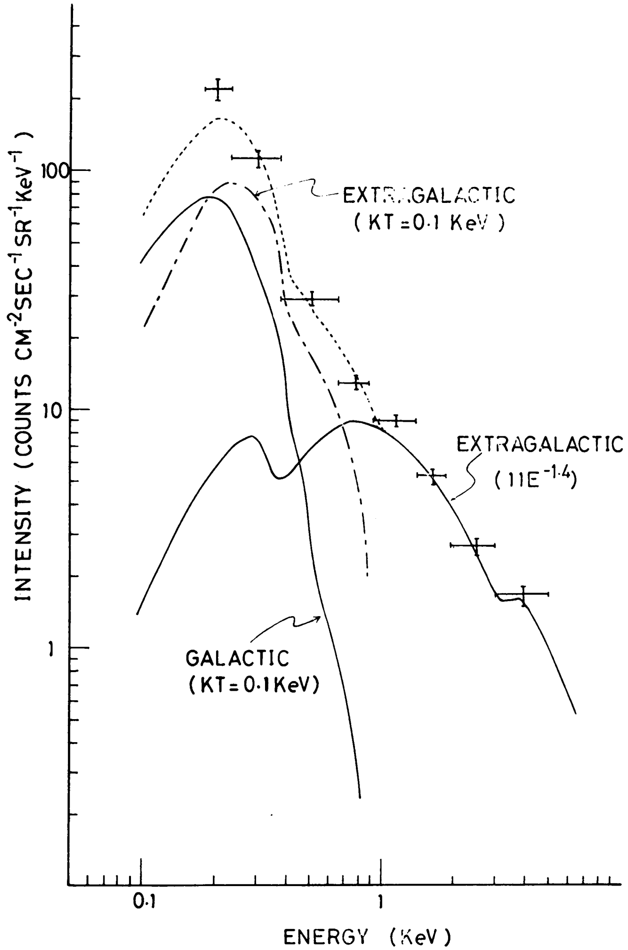

Fig. 6. X-ray spectrum in the high latitude region. The solid curves are the same as those in Figure 5 except for the interstellar absorption, for which $\langle N_H\rangle=3\times10^{20}$ cm^{-2} is assumed. The dot-dashed curve represents the pulse height distribution of the soft extragalactic component. The dashed curve represents the sum of these three components. The observed points are based on the results obtained with the 1 μ LEINAX counters.

5. Ionization of Interstellar Medium

The energy generation rate of soft X-rays is equal to the energy dissipation rate in the interstellar medium. Since the energy per ionization is about 6×10^{-11} erg, the rate of ionization per hydrogen atom caused by X-rays, ζ_x, is given by

$$\zeta_x \simeq G/6 \times 10^{-11}\, n_{\mathrm{H}} \simeq 1 \times 10^{-16}\,\mathrm{s}^{-1} \text{ per H atom}, \tag{8}$$

where the value of G in (7) is substituted to obtain the value of ζ_x. On the other hand, the rate of ionization by cosmic rays is limited by the abundance of Be, which results from the spallation of cosmic ray nuclei colliding with interstellar matter, to (Reeves *et al.*, 1970; Meneguzzi *et al.*, 1971)

$$\zeta_{\mathrm{CR}} \simeq 10^{-17}\,\mathrm{s}^{-1} \text{ per H atom}. \tag{9}$$

These are compared to the ionization rate required for ionization and thermal equilibria for H I regions (Spitzer and Scott, 1969; Goldsmith *et al.*, 1969; Hjellming *et al.*, 1969)

$$\zeta_{\mathrm{H}} \simeq 5 \times 10^{-16}\,\mathrm{s}^{-1} \text{ per H atom}. \tag{10}$$

In view of the fact that the numerical value of ζ_x is subject to uncertainties, such as the ambiguity in distinguishing the galactic component from the extragalactic one and an unknown flux below 0.1 keV, the difference between ζ_x and ζ_{H} given above may not be serious. It is, therefore, likely that the soft X-rays are a main cause of interstellar ionization, as discussed by Sunyaev (1969), by Silk and Werner (1969) and by Werner *et al.* (1970).

The X-rays from individual sources also produce ionization in the vicinity of the sources. The radius of the H II region formed by an X-ray source is limited by its age. In the case of Cygnus Loop the dimension of the H II region is estimated to be smaller than the size of the X-ray source. In view of the fact that most X-ray sources are short-lived, an estimate of the H II region radius under the asumption of the stationary state is not always justified.

6. Mechanisms of Soft X-Ray Production

There are two alternative cases for the spatial distribution of galactic X-ray emissivity, a continuous distribution such as the diffuse matter in interstellar space or a superposition of as yet unresolved sources. There are also two alternative mechanisms of X-ray production, thermal or non-thermal. We shall examine which of four combinations is most likely.

Non-thermal processes in the diffuse matter are most unlikely to be the origin of galactic soft X-rays. If X-rays were emitted by bremsstrahlung of non-thermal particles, the amount of energy spent by these particles for ionization would be several orders of magnitude greater than that for X-rays. As shown in the preceding section, the X-ray energy generation rate is nearly as large as the heating rate required for interstellar matter. The heating rate by the ionization would greatly exceed the latter. In similar arguments other non-thermal processes in interstellar space are ruled out.

The thermal bremsstrahlung could account for the X-ray emissivity if $n_e^2 f = = 10^{-2} - 10^{-3}\ \mathrm{cm}^{-6}$, where f is the fraction of volume in which the electron density is n_e and the electron temperature is $T \sim 10^6$ K. Since the major part of interstellar matter is known to be of much lower temperature, such hot regions would have to be restricted to a small volume. Hence this hypothesis is not different from the case of assuming soft X-ray sources.

A granularity observed by Gorenstein and Tucker (1972) provides evidence against the diffuse distribution of emissivity. They have concluded from the granularity that the source density is about $10^{-2}\ (\mathrm{pc})^{-3}$ or greater and the average luminosity of the sources is about $3 \times 10^{30}\ \mathrm{erg\ s}^{-1}$ in the energy range 0.16–0.28 keV.

The above considerations are in favour of interpreting the diffuse galactic soft X-rays in terms of a superposition of discrete sources which may be stellar and/or nebulous. A number of possible candidates of such sources have been proposed. Since there are too many theories, we here mention only a few of them.

Supernova explosions can supply as much energy as to account for the generation of soft X-rays (Ilovaisky and Ryter, 1971). However, the number density of active SNR's is as small as $10^{-7}\ (\mathrm{pc})^{-3}$, far smaller than that required from the granularity. The angular resolutions in most of the observations available are good enough to resolve such SNR's, which could otherwise contribute to the diffuse component. SNR's could not be responsible for the diffuse soft X-rays, unless their size were as large as or larger than the size of the Gum nebula (Ramaty *et al.*, 1971), so that sky could be covered by a small number of extended SNR's.

The number density increases if old SNR's are included. They may maintain activities due to the matter accretion on to neutron stars. The activities may produce such a hot region around the neutron star that is heated to about 10^6 K (Ostriker *et al.*, 1970; Shvartsman, 1971). This may remain to be a possible candidate, if the galactic emission takes place within the gas disk, in which most of pulsars are found.

Radio spurs may also be responsible for the diffuse soft X-rays, in view of the fact that a strong X-ray emission has been observed in the North Polar Spur (Bunner *et al.*, 1972). Although the enhancement is not so large in nearly the same region scanned by other observations and is not always detectable in other radio spurs (Kato, 1972), the positive result indicates that at least a part, if not all, of diffuse soft X-rays are likely to be associated with radio spurs.

Due to the fact of that the number density of the soft X-ray sources seems to be rather high, the sources may be main sequence stars. Gorenstein and Tucker (1972) have argued that the matter accretion onto a main sequence star results in a temperature of 10^6 K or lower and a matter ring formed in a closed binary system supplies sufficient power to explain the generation of soft X-rays.

Late type main sequence stars are known to produce strong optical and radio flares at a high frequency. They are highly convective, so that their activities are regarded as similar to those of T-Tauri type stars.

Ryter *et al.* (1970) considered thermal bremsstrahlung emitted from the atmosphere of T-Tauri type stars due to the heating by energetic particles that may be responsible for the production of light elements. Grindlay (1970) and Gurzadyan (1971) estimated the intensities of bremsstrahlung X-rays caused at flare stars indirectly and directly by energetic electrons responsible for radio emission, respectively. According to their theories, X-rays of energies greater than 1 keV are also produced and they would result in anisotropies of the diffuse component in the higher energy range. On the other hand, Hayakawa *et al.* (1970) considered the thermal balance of lower corona between the heating by energetic particles and thermal bremsstrahlung loss. Hence a lower corona with the electron density 10^{11} cm^{-3} and the thickness 10^{10} cm can be heated to about 10^6 K and can emit X-rays at a rate of about 10^{30} erg s^{-1}. Taking the flare frequency of once in every hour observed for YZ CMi as representative and the number density of red dwarf stars as 0.1 (pc)$^{-3}$, the average energy output is estimated to be about 3×10^{-28} erg cm^{-3} s^{-1}. Although this is smaller than that required in (7) by an order of magnitude, slight changes in the numerical values of the parameters can increase the theoretically estimated value of the energy generation rate.

Although the sources of the galactic soft X-rays cannot yet be identified in an undisputable way, since too many parameters are left undetermined, it is plausible that the galactic soft X-rays are generated at discrete sources whose density is comparable to the density of stars and that they are emitted by thermal bremsstrahlung of temperature about 0.1 keV.

Acknowledgements

The present review could not be prepared without prompt information from the soft X-ray groups of AS&E, GSFC, LRL at Berkeley, LRL at Livermore, MIT, NRL, Saclay and University of Wisconsin. The author would also like to thank the members of LEINAX who have made unpublished data available. Among them Drs. T. Kato and Y. Tanaka directly helped the author in the preparation of Section 4.

Addendum

After completion of the manuscript, the author received a preprint by A. Davidsen, S. Shulman, G. Fritz, J. F. Meekins, R. C. Henry, and H. Friedman. Their result and its interpretation are in essential agreement with those given in Section 4. Also, Dr Henry made the following comment at the symposium: "E. B. Jenkins (*Bull. Am. Astron. Soc.* **4**, 226, 1972), has observed 8 hot stars in the far ultraviolet and has found, from the strength of interstellar absorption lines, that oxygen and silicon are of canonical abundance, but carbon is apparently 10 × overabundant. H. Friedman and the NRL X-ray astronomy group (*Astrophys. J.* **174**, 389) have found a stronger absorption of soft X-rays from the Crab than the 21-cm column density and canonical abundances predict; the discrepancy would be substantially moderated if carbon were actually 10 × overabundant in the interstellar medium."

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