PART VI

PHYSICAL PROCESSES, THEORY AND EXPERIMENT

COSMIC X-RAYS AND INTERSTELLAR DUST

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Abstract. Observational results of cosmic diffuse X-rays are reviewed with particular emphasis on soft X-rays. The intensity distribution of soft X-rays over the celestial sphere indicates that the diffuse component of soft X-rays consists of an extra-galactic and a galactic component. The absorption of the soft X-rays in the interstellar medium results in heating and ionization of interstellar matter. The ionization rate by X-rays is estimated as about 10^{-16} s^{-1} per H atom.

The scattering of X-rays by interstellar dust grains produces a halo of an X-ray source and smears out the pulsation of X-ray emission. The scattering coefficient and the halo size are given for some typical grain models.

The possibility that the dust grains gain relativistic energy is suggested. It is speculated that the relativistic dust grains in metagalactic space may be responsible for cosmic rays of ultrahigh energies and also for the diffuse X-rays by the interactions with cosmic black-body radiation.

1. Introduction

Since the discovery of cosmic X-rays ten years ago, little attention has been paid to the relevance of cosmic X-rays to interstellar dust. This is due to the facts that the energy density of X-rays in interstellar space is much smaller than that of radiation in a longer wavelength range, and that the interstellar medium is practically transparent for the X-rays of energies greater than 1 keV.

The extension of observation of cosmic X-rays to lower energies has changed this situation. It has been noted that the amount of energy dissipated by soft X-rays in interstellar matter may be comparable to or even greater than that by other agencies such as low energy cosmic rays. Further, the scattering of soft X-rays by interstellar dust grains may be of some astronomical relevance to studies of cosmic X-rays and interstellar dust.

The present article deals with three rather separate topics. The first part is devoted to a review of the diffuse component of cosmic X-rays and its contribution to the heating and ionization of interstellar matter. Recent observations have indicated that a substantial part of soft X-rays are generated in our Galaxy and then absorbed by the interstellar matter. The ionization rate is estimated to be comparable to that required for maintaining the temperature of the interstellar matter.

In the second part the scattering of X-rays by interstellar dust grains is discussed. The scattering results in a halo of a point X-ray source and in smearing out X-ray pulsations thereof. Hence the observations of soft X-rays from point sources will provide means of obtaining their distances as well as the size and the density of the dust grains.

The third part is so speculative that its validity remains to be examined by further

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investigation. It is speculated that dust grains are accelerated in active galaxies with compact nuclei. Relativistic dust grains injected into intergalactic space may be responsible for cosmic ray air showers of very large size and may also produce X-rays by interactions with cosmic microwave radiation.

2. Diffuse Component of Cosmic X-Rays

Cosmic X-rays consist of the diffuse component and the component associated with individual sources. The diffuse component may result from a superposition of as yet unresolved sources, but its distribution over the celestial sphere is essentially isotropic at energies above 2 keV in contrast to the strong concentration of galactic X-ray sources towards the galactic plane. Hence it is inferred that galactic sources contribute little to the diffuse component, whereas extragalactic sources may contribute considerably to the diffuse component. This implies that the diffuse component belongs to the metagalaxy and its interactions with our Galaxy are very weak.

The spectrum of the diffuse component has been measured over a wide energy range. Since the observational results in the energy range 1–30 MeV remain to be confirmed, our discussions are restricted to the range below 1 MeV. Some controversy still exists in this energy range, but the spectrum shown in Figure 1 gives its general trend.

The spectrum is represented by a power law with a change in its slope near 40 KeV. The energy at which the slope changes and the rate of change are not well established, since most observations at energies above 25 KeV have been made at balloon altitudes and the correction for the scattering effect in the atmosphere is complicated, but the steepening of the spectrum is unmistakable from the low absolute intensity around 100 KeV.

Below 40 KeV the spectrum would appear to be represented by a single power law of $E^{-1.8}$, where E is the energy of an X-ray photon. However, more detailed examination shows that a flatter spectrum $E^{-1.4}$ is favoured in the energy range 1.5 to 10 KeV, and that the spectrum at energies below 1 KeV depends on the direction of sight.

In the soft X-ray region the diffuse component is not isotropic. A summary of several sky surveys (Kato, 1972) has shown that the intensity of soft X-rays generally increases with galactic latitude except in several selective regions. Recent sky surveys (Bleeker *et al.*, 1973; Hayakawa, 1972b; Davidsen *et al.*, 1972) have also confirmed this tendency. The latitude dependence is most clearly observed in the anticenter region, where few enhanced regions are found. In other directions the intensity distribution is complex and several enhanced regions are observed. The enhancement towards the galactic center may be contaminated by sources. This decreases as energy decreases and vanishes in the energy range 0.23–0.37 KeV. The enhancement around $l \sim 330°$ and $b \sim 20°$ is strong in the entire energy range below 1 KeV. The distributions in the energy ranges 0.37–0.65 keV and 0.65–0.90 KeV are given by Hayakawa (1972b) and the distribution in the range 0.23–0.37 KeV is shown in Figure 2, all based on the LEINAX sky survey by the Leiden-Nagoya collaboration experiment. A similar result is obtained by Davidsen *et al.* (1972) in the anticenter region.

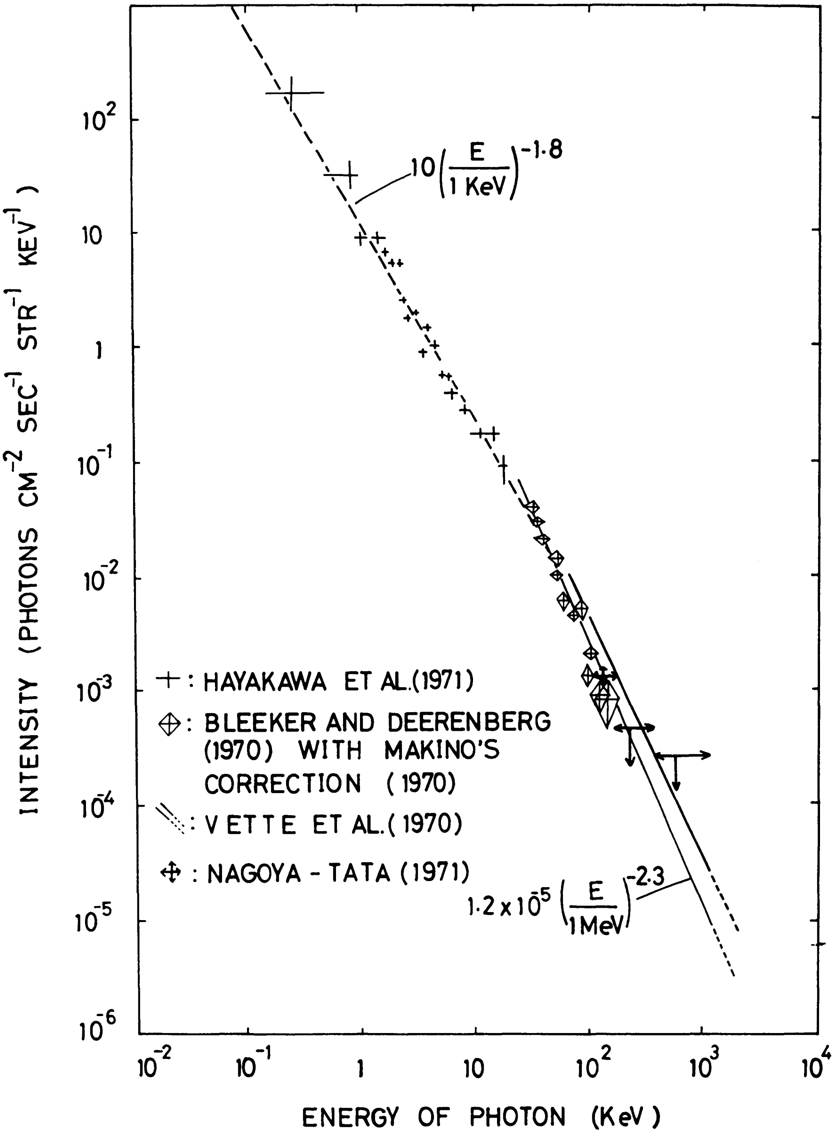

Fig. 1. The energy spectrum of cosmic diffuse X-rays. Two lowest energy points are taken from the intensities at high galactic latitudes. As described in the text, the intensity in such a low energy region depends on the direction of sight.

The galactic latitude dependence of the soft X-ray intensity may be interpreted in terms of the absorption of extragalactic X-rays by interstellar matter (Kato, 1972; Hayakawa, 1972b; Davidsen *et al.*, 1972). Further analysis of the LEINAX result supports the above conclusion for the hydrogen column densities greater than 10^{21} atoms cm^{-2}, as shown in Figure 3. At greater hydrogen column densities the intensity observed is higher than that expected from the interstellar absorption of extragalactic

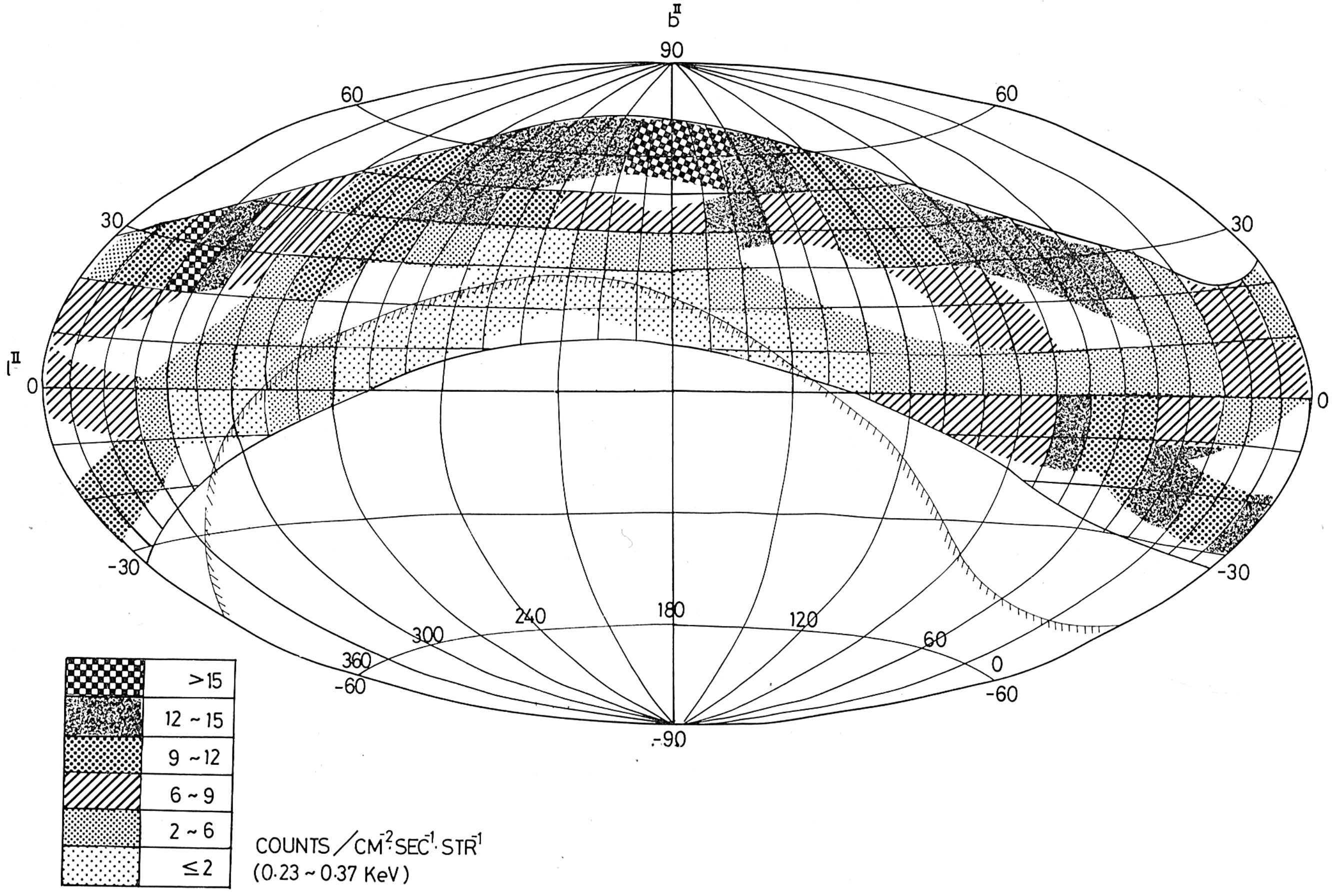

Fig. 2. The distribution of soft X-rays over the celestial sphere, prepared by T. Kato, based on the Leiden-Nagoya collaboration experiment. The energy range 0.23–0.37 keV represents the pulse height range of the counters. The energy range of X-rays is greater, since the energy resolution of the counters at 0.28 keV is 64%.

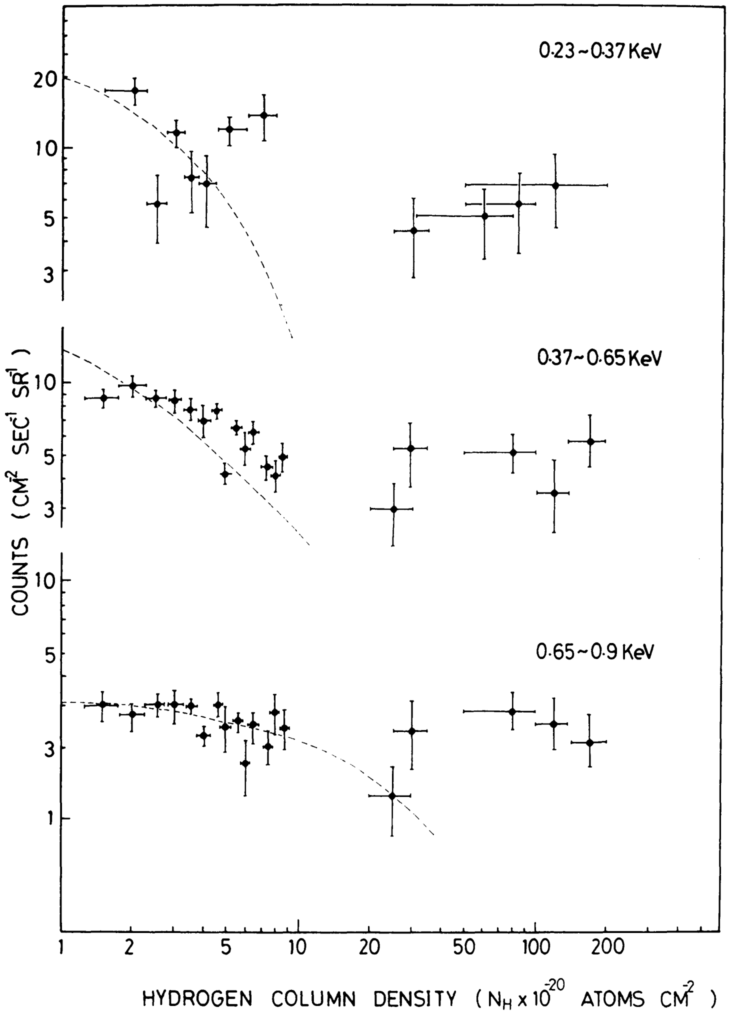

Fig. 3. The X-ray intensity versus the hydrogen column density. The energy ranges indicated represent the pulse height ranges. The dashed curves represent the theoretical absorption curves for extragalactic X-rays.

X-rays. The excess intensity at low galactic latitudes can be attributed to the emission of soft X-rays in our Galaxy.

The distribution of the soft X-ray emissivity in our galaxy remains to be further investigated; it seems to form a disk a little thicker than the gas disk. At low galactic latitudes the extragalactic component and the galactic component generated far from the galactic plane are negligible because of the interstellar absorption and, consequently, the emissivity of the galactic component can be obtained nearly independently of the thickness of the X-ray disk. The intensity of the extragalactic component is obtained by modifying the $E^{-1.4}$ spectrum extended to low energy by the absorption through the interstellar gas of the hydrogen column density 3×10^{21} atoms cm^{-2}. As seen from Figure 4, the contribution of the extragalactic component in the soft X-ray region is indeed negligible. The conclusion hardly depends on the extrapolation of the extragalactic spectrum to low energy and on the possible contribution of the galactic

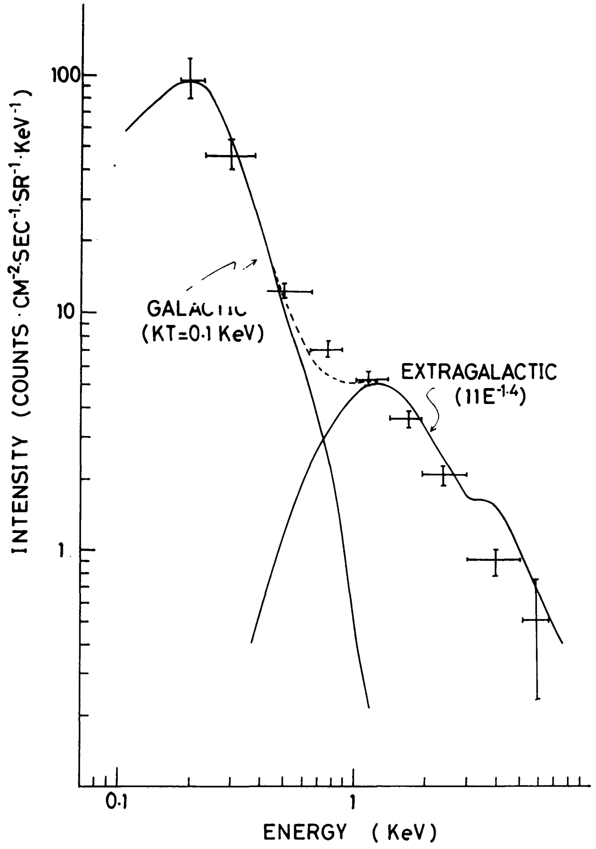

Fig. 4. The energy spectrum of diffuse X-rays at a low galactic latitude. The solid curves represent the pulse height spectra for the $E^{-1.4}$ extragalactic spectrum and the $E^{-1}\exp(-E/kT)$ galactic spectrum at the hydrogen column density of 3×10^{21} cm^{-2}. The dashed curve represents their sum.

X-rays generated far above the galactic plane. The difference between the intensities observed and of the extragalactic component gives the intensity of the galactic component, which is also given in Figure 4.

The X-ray emissivity is derived from the intensity of the galactic component, taking the interstellar absorption into account. The solid line drawn for the spectrum of the galactic component is obtained from the emissivity

$$g(E) = g_0 n_H E^{-1} \exp(-E/kT) \text{ photons cm}^{-3}\,\text{s}^{-1}\,\text{keV}^{-1} \qquad (1)$$

with n_H = number of H atoms per cm^3.

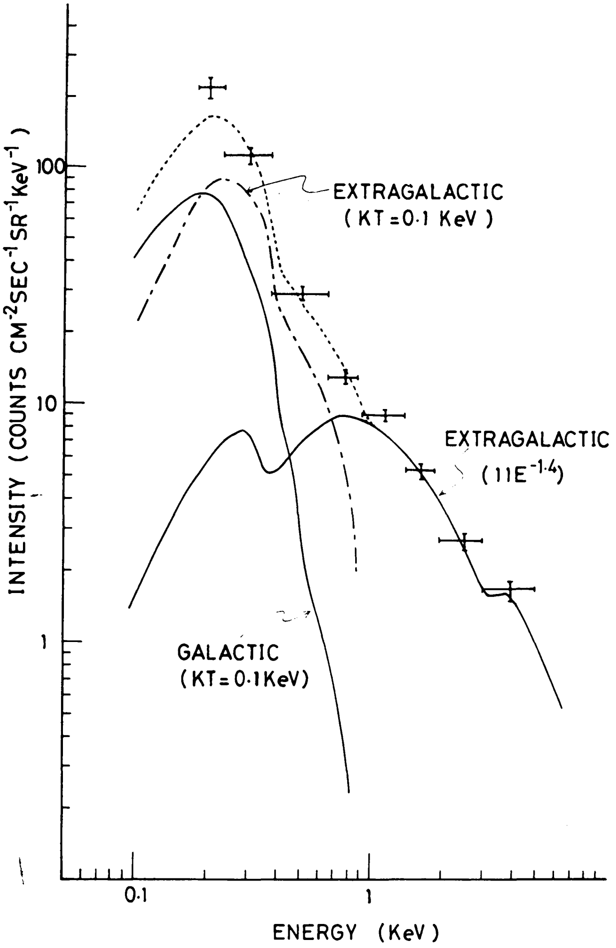

Fig. 5. The energy spectrum of diffuse X-rays at high galactic latitude. The solid curves are the same as in Figure 4, but different in the hydrogen column density, 3×10^{20} cm^{-2}. The dot-dashed curve represents the extragalactic E^{-1} exp $(- E/kT)$ spectrum subject to the interstellar absorption. The dashed curve represents the sum of these three components.

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

and taking into account the efficiency and the energy resolution of the counters.

The expression (1) simulates the free-free emission. Actually, however, the emission lines are stronger by an order of magnitude than the continuum at such a low temperature. Hence the expression (1) should be regarded as an empirical relation holding for $E \gtrsim 0.2$ KeV, since the generation spectrum for $E < 0.2$ keV is obscured by the interstellar absorption. Indeed, the spectrum obtained by folding the emission lines by the energy resolution of the counters is approximately expressed by the expression (1) with a slightly higher temperature, except in a few narrow ranges in which strong emission lines lie. The folded spectrum falls off towards low energy for $E \lesssim kT$, since the probability of line excitation decreases.

If the emissivity (1) is assumed to hold in the galactic disk, the contribution of the galactic X-rays to the diffuse component at high latitudes can be computed, as given for the hydrogen column density of 3×10^{20} atoms cm^{-2} in Figure 5. The difference between the intensity observed and that of the galactic component gives the intensity of the extragalactic component.

The theories that have been proposed to explain the origin of the soft galactic X-rays have been discussed elsewhere. (Hayakawa, 1972b). Here we only point out that they may be generated by discrete sources of a rather high number density. This is based on the observations by Gorenstain and Tucker (1972) and by Davidsen *et al.* (1972) that a granularity of the intensity distribution exists but is less than expected if the galactic X-rays were due to a superposition of a few discrete sources, so that the probability of finding no source in the field of view would be high. The source density is thus estimated to be as large as 10^{-2}–10^{-3} pc^{-3}.

Accordingly the soft X-rays are absorbed rather uniformly by interstellar matter. Since the absorption coefficient is large at low energies, as shown in Figure 6, the rate of energy dissipation in the interstellar medium is nearly equal to the rate of energy generation. The latter is obtained from Equation (1) as

$$G = \int Eg(E)\,\mathrm{d}E \simeq 5 \times 10^{-27}\, n_{\mathrm{H}}\,\mathrm{erg\,cm^{-3}\,s^{-1}}. \tag{2}$$

An overestimate due to the extension of the integral to $E < kT$ is nearly compensated by the omission of bumps in excess of the expression (1) due to emission lines.

The energy dissipation rate, which is equal to G, is divided by the energy per ionization, 6×10^{-11} erg, to give the rate of ionization per hydrogen atom

$$\zeta_{\mathrm{X}} \simeq 1 \times 10^{-16}\,\mathrm{s^{-1}}\ \text{per H atom}. \tag{3}$$

This is greater than the rate of ionization by cosmic rays, which, on the assumption that the spallation of cosmic ray nuclei colliding with interstellar matter gives the galactic abundances of Be and B, is estimated at

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

The value of ζ_{X} must be compared to the ionization rate required for the ionization and thermal equilibria for H I regions (Spitzer and Scott, 1969)

$$\zeta_{\mathrm{H}} \simeq 5 \times 10^{-16}\,\mathrm{s^{-1}}\ \text{per H atom}. \tag{4}$$

The difference between ζ_{X} and ζ_{H} may not be serious in view of uncertainties in the values of parameters necessary for deriving the value of ζ_{X}. Since the value of ζ_{X} in Equation (3) is based on the X-ray intensity in the anticenter region, a larger value is obtained in the regions where the X-ray intensity is stronger than in the anticenter region. Although the conclusion is not yet quantitative, the soft X-rays are responsible for a substantial part of the heating and ionization of interstellar matter.

3. Scattering of X-Rays by Dust Grains

The absorption coefficient in Figure 6 is obtained under the assumption that all interstellar atoms are in the gas phase. If some of them form solid grains and their size is comparable to or greater than the absorption mean free path, the extinction coefficient for X-rays is reduced since the absorption in the grain is saturated. However, this is not the case since the interstellar dust grains are believed to be of submicron size, which is smaller than the absorption mean free path of X-rays with energies down to 0.1 keV.

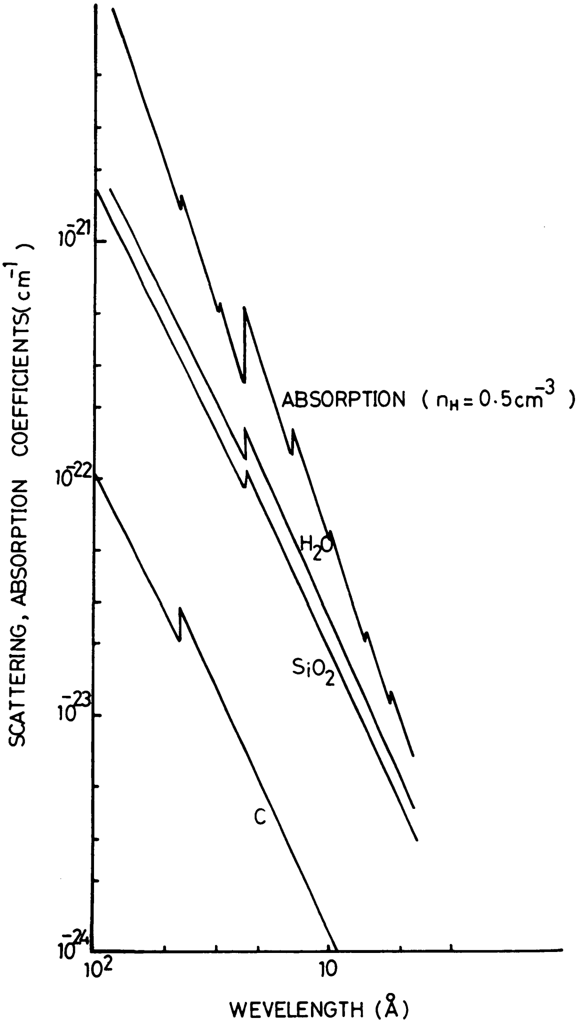

Fig. 6. The scattering and the absorption coefficients of X-rays in the interstellar medium. The absorption coefficient is based on the calculation for the hydrogen density $n_H = 0.5\ \text{cm}^{-3}$ by Brown and Gould (1970). The scattering coefficients by dust grains are based on the calculation for C ($a = 0.05\ \mu$), SiO_2 ($a = 0.08\ \mu$) and H_2O ($a = 0.14\ \mu$) by Hayakawa (1970).

The scattering of X-rays by dust grains has been discussed from various aspects by Overbeck (1965), by Slysh (1969), by Naranan and Shah (1970), by Ryter (1970), and by Hayakawa (1970). The differential scattering cross section for an X-ray of wavelength λ is obtained by the Rayleigh-Gans approximation as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = 2a^2\left(\frac{2\pi a}{\lambda}\right)^4 |m-1|^2\left|\frac{j_1(x)}{x}\right|^2(1+\cos^2\theta), \tag{5}$$

where $j_1(x)$ is the spherical Bessel function of the first order, $x = (4\pi a/\lambda)\sin(\theta/2)$ and θ is the cattering angle. Here the dust grain is assumed as *a* sphere of radius a and with the complex diffraction index m. The total scattering cross section is given by

$$\sigma = 2\pi a^2\left(\frac{2\pi a}{\lambda}\right)^4 |m-1|^2 = 2\pi a^2\left[(r_e\lambda a n_e)^2+\left(\frac{\mu a}{2}\right)^2\right], \tag{6}$$

where r_e is the classical electron radius, n_e the electron density and μ the absorption coefficient in the grain. The scattering coefficients σn_g, where n_g is the number density of the interstellar grains, are compared with the absorption coefficient in Figure 6 (Hayakawa, 1970). Here three representative grain models are adopted, i.e., ice of $a = 0.14\ \mu$, silicate of $a = 0.08\ \mu$ and graphite of $a = 0.05\ \mu$. For $n_g = 1\times10^{-12}$ cm^{-3}, the scattering coefficient is small compared to the absorption coefficient and may be comparable to the possible error of the latter associated with the uncertainties in the interstellar hydrogen density and the chemical composition of interstellar matter.

The angular distribution given by the expression (5) is nearly flat for $x < 1$ and falls off as θ^{-4} for $x \gg 1$. The half width of the distribution is about $x = 1.8$, corresponding to

$$\theta_h = 7.4\times10^2(1\,\mathrm{keV}/E)(0.1\mu/a)\,\mathrm{arc\,s}. \tag{7}$$

This demonstrates that the image of a point X-ray source forms a halo of radius θ_h. The brightness of the halo relative to the intensity of the direct image of the source is proportional to $\sigma n_g l/\exp(-\sigma n_g l)$, provided that the source distance l is not so large that the multiple scattering is negligible.

Another effect of the dust grains is the time delay of the propagation of X-rays. The average time delay for X-rays scattered through an angle θ is

$$\Delta t = l\theta^2/4. \tag{8}$$

Since the time delay is appreciable even for a scattering angle as small as one arc second, this effect is observable even when the angular resolution is good enough to resolve the halo from the core in the image of a source.

These effects are important not only for X-ray astronomy but also provide a novel means of studying the interstellar dust. Since the scattering cross section increases as the X-ray energy decreases, the effects are dominant in the soft X-ray region, in particular in the energy range just below the absorption edge of oxygen. The halo size gives direct information on the grain size. Once the size of known, the brightness of the halo and the decrease of the relative intensity of the pulsating component give the value of

$\varrho^2 n_g l$, where ϱ is the density of the grain. These effects can be observed by the technique available at present. Further development in technology will make it possible to observe further detail of interstellar dust grains.

4. Dust Grains of Relativistic Energies

Although the dust grains will mainly move with the interstellar gas, because of the short mean free path of collisions between dust grains and atoms in a gas, a small fraction of the dust grains may acquire high energies, as about 10^{-9} of the interstellar diffuse atoms form cosmic rays. Nearly a quarter century ago, Spitzer (1949) suggested that heavy nuclei discovered in primary cosmic rays could be explained by relativistic dust grains of meteoritic composition that impinged into the atmosphere and then evaporated into atoms. He suspected that such grains could be accelerated by a strong radiation pressure caused by supernova explosions. Although the acceleration to relativistic energy was found to be difficult because of the retardation effect, acceleration by moving magnetic fields may operate after the injection to semi-relativistic energy by radiation pressure, since the dust grains are supposed to be charged. The behaviour of a dust grain after it gains energy exceeding the critical injection energy may be essentially the same as that of nuclear particles and electrons. Below this energy the dust grain may be decelerated or may even be destroyed by collisions with ambient matter.

The injection by radiation pressure may take place in the compact cores of active galaxies, such as quasistellar objects and Seyfert galaxies. If the radiation is as strong as 10^{45} erg s^{-1} and is emitted from a compact source as small as several light months, the Lorentz factor of a grain, γ, becomes appreciably greater than unity, though it hardly exceeds $\gamma = 10$. Since these objects are known to be strong radio sources, the magnetic acceleration responsible for generating relativistic electrons which emit radio waves by the synchrotron radiation may also be responsible for the further acceleration of the dust grains. The magnetic regidities of the dust grains accelerated may exceed 10^{17} V, if their charge is 10^2 to 10^3 times the unit electric charge. The acceleration to such high rigidity is considered to be possible, since the magnetic fields in the active galaxies may be stronger than in our Galaxy and the sizes of the radio emitting regions are larger than the dimension of our Galaxy. If these dust grains escape into intergalactic space, they form a part of metagalactic cosmic rays.

Thus Hayakawa (1972a) has speculated that the relativistic dust grains are responsible for extensive air showers of sizes greater than 10^{10}. It has been generally believed that such large extensive air showers are produced by metagalactic protons of energies greater than a few times 10^{19} eV, because of their essential isotropy and of the difficulty of being trapped in our Galaxy. A serious objection has, however, been raised against this interpretation. In the rest system of the protons, the energies of photons of the cosmic black-body radiation are high enough to produce mesons and, as a result, the protons would lose their energy so rapidly that the spectrum of the protons should fall off steeply beyond a few times 10^{19} eV. On the other hand, the size spectrum of extensive air showers does not fall off but maintains it slope beyond the size of 10^{11}.

If the extensive air showers are originated by the dust grains, the energy loss by meson production does not take place, since the Lorentz factors are of the order of 10^3. The total energy of a dust grain of $\gamma \simeq 10^3$ is large enough for the production of huge extensive air showers, since a grain of radius 0.1 μ contains about 10^{10} nucleons. The flux of the relativistic dust grains is estimated under the assumptions that the intensity of metagalactic cosmic rays is 10^{-3} times that of the galactic ones, and that the grain to proton ratio at a given value of γ is the same as that in the interstellar medium, that is, 10^{-12}. Since the proton intensity observed for $\gamma \geqslant 10^3$ is about 10^{-5} cm^{-2} s^{-1} sr^{-1}, the flux of metagalactic dust grains of $\gamma \geqslant 10^3$ is expected to be about 10^{-20} cm^{-2} s^{-1} sr^{-1}. This is nearly the value required for the frequency of extensive air showers of the sizes greater than 5×10^{10}.

It should, however, be remarked that the relativistic dust grains lose energies by interaction with the cosmic black-body radiation, and that the scattering of the black-body photons and the thermal emission of the grains contribute to metagalactic X-rays.

The average energy of the black-body photons is $\varepsilon \sim 10^{-3}$ eV. In the rest system of the dust grain the photon energy is of the order of $\gamma\varepsilon$. Since this is in the visible and near infrared ranges, these photons are scattered and absorbed with a cross section close to the geometrical one. The photons scattered have energies as large as $\gamma^2\varepsilon$, which is about 1 keV for $\gamma = 10^3$. The temperature of the grain is of the order of 10^2 K and the thermal photons for $\gamma = 10^3$ is as high as some tens of eV. Since the density of the black-body photons is of the order of 10^3 cm^{-3}, the scattering cross section of 10^{-10} cm^2 gives the X-ray flux of about 10 cm^{-2} s^{-1} sr^{-1}, if the contribution over the cosmic radius of 10^{28} cm^2 is taken into account. The thermal emission gives a higher flux in the XUV region.

A quantitative analysis, which will be published elsewhere, gives the following results. The energy loss of a relativistic dust grain is dictated by absorption for $\gamma < 10^3$, whereas the scattering is a dominant cause for $\gamma > 10^3$. This is because the scattering cross section increases steeply with the energy of the incident photon and levels off in the visible region, whereas the absorption cross section is supposed to be proportional to the photon energy over a wide range of the energy. The fractional energy loss over the cosmic age approaches unity at $\gamma = \gamma_c$, so that the spectrum of the dust grains becomes steeper for $\gamma > \gamma_c$. In this range the scattering is dominant over the absorption, and the grains of inital γ greater than γ_c are degraded to γ_c.

The flux of the dust grains is estimated under the assumptions that the intensity of primary particles producing extensive air showers of sizes greater than 5×10^{10} is 3×10^{-20} cm^{-2} s^{-1} sr^{-1}, and that the energy required for a shower particle is 2×10^{10} eV, taking into account the fact that the energy of a primary nucleon is as low as 10^{12} eV. Thus the differential spectrum of the relativistic dust grains is approximately expressed as

$$j(\gamma) = j_0\gamma^{-\alpha} + j_c\delta(\gamma - \gamma_c) \quad \text{for} \quad \gamma \leq \gamma_c, \tag{9}$$

with

$$j_0 = 1 \times 10^{-16}(0.1\mu/a)^{3(\alpha-1)}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1},$$
$$j_c = j_0/(\alpha-1)\gamma_c^{\alpha-1}, \quad \gamma_c = 2 \times 10^3(0.1\mu/a), \quad \alpha \simeq 1.6,$$

where a is the radius of the grain. The term with the δ-function may oversimplify the actual spectrum, the latter being peaked at about γ_c and having some width.

The contribution to the scattered photons comes mainly from the δ-function term, and the spectrum of photons is a black-body spectrum with a temperature of about $\gamma_c{}^2\,T_b$, where T_b is the temperature of the cosmic black-body radiation. The maximum of the spectrum appears at

$$E_m \simeq 0.8(0.1\mu/a)^2\,\mathrm{keV}, \tag{10}$$

and the flux at E_m is

$$f_s(E_m) \simeq 0.2(0.1\mu/a)^{1.2}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{keV}^{-1}. \tag{11}$$

If a is as small as 0.03 μ, this agrees with the observed X-ray flux, but the spectrum falls off toward high energy more rapidly than the observed one.

The thermal emission gives a flux

$$f_{th}(E) \simeq 1 \times 10^2(0.1\mu/a)^{3,3}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{keV}^{-1}, \tag{12}$$

and its spectrum is nearly flat for $E \lesssim 0.1\,(0.1\mu/a)^{1.2}$ keV. This is in approximate agreement with the flux of the soft extragalactic component described in Section 2.

These results rather critically depend on the optical properties of the dust grains in the near infrared region. The artificial separation of the spectrum in two parts, as shown in Equation (9), is due partly to the lack of knowledge about the optical properties. The spectra obtained in Equations (11) and (12) are greatly affected by this artificial assumption as well as by the simplification in the kinematics of scattering and thermal emission. Hence they should be regarded as giving rough values of the X-ray fluxes in the two energy regions.

The existence of the relativistic dust grains discussed in this section is merely speculative and its reality will have to be explored by future studies. It may, however, be instructive to bring up this speculative theory, since it emphasizes the important bearing of the dust grains on various astrophysical phenomena.

Acknowledgements

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References

Bleeker, J. A. M. and Deerenberg, A. J. M.: 1970, *Astrophys. J.* **159**, 215.
Bleeker, J. A. M., Deerenberg, A. J. M., Yamashita, K., Hayakawa, S., Kato, T., and Tanaka, Y.: 1973, in preparation.

Brown, J. and Gould, R. J.: 1970, *Phys. Rev.* **D1**, 2252.
Danjo, A., Hayakawa, S., Ideka, M., Makino, F., Tanaka, Y., Agrawal, P. C., Gokhale, G. S., and Sreekantan, B. V.: 1970, *Space Research* **XI**, 1373.
Davidsen, A., Shulman, S., Fritz, G., Meekins, J. F., Henry, R. C., and Friedman, H.: 1972, *Astrophys. J.* **177**, 629.
Gorenstein, P. and Tucker, W. H.: 1972, *Astrophys. J.* **176**, 333.
Hayakawa, S.: 1970, *Prog. Theor. Phys.* **43**, 1224.
Hayakawa, S., Kato, T., Makino, F., Ogawa, H., Tanaka, Y., Yamashita, K., Matsuoka, M., Miyamoto, S., Oda, M., and Ogawara, Y.: 1971, *Astrophys. Space Sci.* **12**, 789.
Hayakawa, S.: 1972a, *Astrophys. Space Sci.* **16**, 238.
Hayakawa, S.: 1972b, in H. Bradt and R. Giacconi (eds.), 'X- and Gamma-Ray Astronomy', *IAU Symp.* **55**, 235.
Kato, T.: 1972, *Astrophys. Space Sci.* **16**, 478.
Makino, F.: 1970, *Astrophys. Space Sci.* **8**, 251.
Naranan, S. and Shah, G. A.: 1970, *Nature* **225**, 836.
Overbeck, J. W.: 1965, *Astrophys. J.* **141**, 864.
Ryter, Ch.: 1970, *Nature* **226**, 1040.
Slysh, V. I.: 1969, *Nature* **224**, 159.
Spitzer, L.: 1949, *Phys. Rev.* **76**, 583.
Spitzer, L. and Scott, E. H.: 1969, *Astrophys. J.* **158**, 161.
Vette, J., Gruber, D., Matteson, J. L., and Peterson, L. E.: 1970, *Astrophys. J.* **160**, L161.