DIFFUSE COSMIC X- AND GAMMA RADIATION: THE ISOTROPIC COMPONENT*

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1. Introduction

The discovery of the first galactic X-ray source occurred in 1962. Simultaneously, the early rocket flights detected a strong diffuse X-ray component, and soon revealed the remarkable degree of isotropy of the background X-rays. There have been many observations in recent years of the diffuse X-ray flux, spanning the energy range $\frac{1}{4}$ keV to 100 MeV. Figure 1 shows the presently available data. Note that I have discarded some of the older observations, in particular where the same group has obtained new data. The data are plotted in energy units, in order to compress the vertical scale, and accentuate the spectral features that are apparent. These units (i.e., keV cm^{-2} sec^{-1} ster^{-1} keV^{-1}) are used throughout this review, unless otherwise stated.

The best evidence for a change in slope is for the 40 keV break. An experiment on

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board the OSO 3 satellite (Schwartz *et al.*, 1970) has data spanning the range from 10 to 100 keV, and provides perhaps the best confirmation to date of the reality of a $\sim\frac{3}{4}$ power break in the spectrum at about 40 keV. Most groups seem to agree on the slope below 10 keV, although normalization is a problem. The $\frac{1}{4}$ keV data is still fairly discrepant, and ranges from 50 to 400 keV (cm^2 sec ster keV)$^{-1}$, in the maximum fluxes reported by different groups.

However only one reported flux at 0.25 keV (Baxter *et al.*, 1969) exceeds $\sim$150 keV/cm^2 sec ster keV. Part of the discrepancy in the remaining experiments may be caused by contributions from weak unresolved galactic soft X-ray sources (Oda, 1969). In addition a correction for interstellar absorption must be made, which according to Bowyer *et al.* (1968) is negligible, and according to Henry *et al.* (1968) amounts to

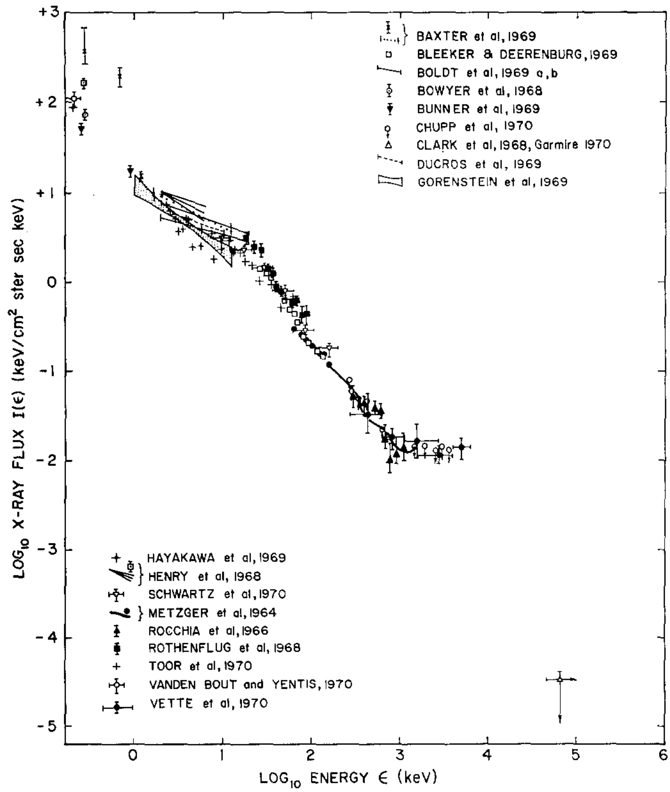

Fig. 1. Observations of the isotropic X-ray background. All available recent observations over the range $\frac{1}{4}$ keV to 100 MeV are included. The points near 0.25 keV represent fluxes measured at high galactic latitudes, and are *uncorrected* for either interstellar absorption, or for a possible contribution from unresolved weak galactic sources. The observations between 200 keV and 10 MeV are measured with omnidirectional detectors: consequently little is known about the isotropy of these X- and γ-rays. Moreover, only the energy loss response of the detector in this energy range is shown: determination of the actual photon flux requires a specific assumption about the form of the spectrum. The observations of Chupp *et al.* (1970) are made with a balloon-borne detector under $\sim$ 4 g/cm^2 of atmosphere, and so represent only an upper limit to the cosmic γ-ray flux. The fluxes plotted are in units of keV/cm^2 sec ster keV, and are obtained from the published data by taking the product of the photon flux over a given energy channel with the mean energy of that channel.

a factor of ~ 3. In principle, the correction for interstellar absorption can be measured directly by scanning perpendicular to the galactic plane. However uncertainty in the cloud structure of interstellar neutral hydrogen allows the possibility, for example, of extreme small-scale clumpiness of the H I which would be consistent with the 21 cm observations, and yet allow an anomalously low absorption at 0.25 keV (Bowyer and Field, 1969). The most recent results (Bunner *et al.*, 1969, 1970; Vanden Bout and Yentis, 1970) reveal evidence for a significant contribution to the high latitude flux in excess of the power-law extrapolation from keV energies. Finally, above 1 MeV, and most uncertain of these features, is a possible flattening of the γ-ray spectrum (Vette *et al.*, 1970). Roughly speaking, the energy spectrum $\sim E^{-1} - E^{-2}$ from $\frac{1}{4}$–1 keV; $\sim E^{-0.5}$ from 1–10 keV; $\sim E^{-0.75}$ for 10–40 keV; $\sim E^{-1.3}$ from 40 keV–1 MeV; $\sim E^{0}$ from 1–6 MeV, and $\sim E^{-2}$ from 6–100 MeV. It should be emphasized that between 1 keV and 1 MeV the spectrum shows no evidence for any distinct break: rather, there appears to be a gentle curvature. Only asymptotically do there appear to be real changes in spectral index.

There are only two probable observations of isotropic γ-rays, both satellite experiments, by Vette *et al.* (1970) from 1–6 MeV, and by Clark *et al.* (1968) at ~ 100 MeV. The former observation was made with an omni-directional detector; consequently, there is no evidence on the isotropy of the measured γ-radiation. The 100 MeV observation is now considered to be an upper limit on the isotropic flux, rather than an absolute measurement at this energy (Garmire, 1970).

The early interpretations of these diffuse X-rays concentrated on explaining the X-ray flux, and either ignored the spectrum or assumed a constant slope. Although considerable uncertainty exists in the spectral index of the diffuse X-radiation above ~ 300 keV, owing to the necessity of unfolding the actual photon spectrum from the energy loss spectrum of the detectors (Anand *et al.*, 1969; Trombka, 1970), there seems to be little doubt concerning the reality of the 40 keV break and the $\frac{1}{4}$ keV excess.

Any interpretation of the origin of the diffuse X- and γ-ray background must account for the spectrum as well as the flux, and in this review I shall pay particular attention to the spectral predictions of the various theories.

Perhaps the primary reason for an extragalactic origin of the diffuse X-rays lies in their isotropy. Apart from the disc component, the diffuse X-rays between 10 and 100 keV are isotropic to better than 5% over angular scales of 10° (Schwartz, 1970). In particular, less than 3% of the diffuse X-rays can be produced in a galactic halo model (radius 12 kpc) of their origin (Hamilton and Francey, 1969).

The extragalactic origin of the X-ray background has been impressively demonstrated by the increase in soft X-ray flux with increasing galactic latitude due to the effects of interstellar absorption, first reported by Bowyer *et al.* (1968), and confirmed by several other groups. Although some part of the $\frac{1}{4}$ keV flux may be of galactic origin, it seems clear that most of the flux observed at high latitudes must originate outside the galactic disc.

Isotropic radiation must come, at least in part, from exceedingly remote distances, because for a uniform isotropic distribution of cosmic sources of constant absolute bright-

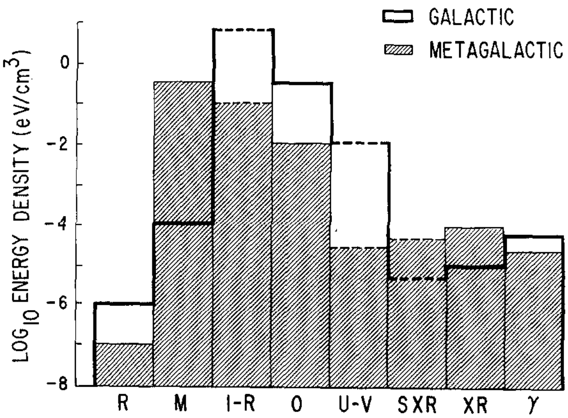

Fig. 2. Where the cosmic photons are. Estimates of the flux of electromagnetic radiation in different spectral regions, plotted in histogram form and in units of eV/cm^3. The spectral regions considered are radio (R), microwave (M), infrared (I–R), optical (O), ultraviolet (U–V), soft X-ray (SXR), X-ray (XR), and γ-ray (γ) wavelengths. Fluxes are shown in the thatched regions for the galactic contribution in the solar neighbourhood, and under the heavy line for an average point in intergalactic space. This histogram compares, in effect, the surface brightness of the Milky Way (after subtracting the surface brightness of the galactic poles) with that at the galactic poles. Estimates for those spectral regions where considerable uncertainty still exists are shown as dashed lines.

ness, both the very distant sources and the nearby sources make a similar contribution to the diffuse flux. Hence the cosmological significance of the diffuse X-ray background.

What is even more remarkable about the diffuse X-rays is that the isotropic background between 1 and 100 keV greatly exceeds in intensity the emission from the Milky Way at these energies. Only in one other region of the spectrum does one find a similar result. Figure 2 shows a histogram, in which rough estimates are plotted of the flux of electromagnetic radiation in units of photon energy density (in eV per cm^3) for several different wavelength regions. The unshaded columns denote the average photon density produced by our own galaxy, evaluated for the solar neighbourhood. This is compared with the mean photon density in the Metagalaxy (denoted by the shaded regions), where only contributions from distant sources are included. Note that in most spectral regions, the galactic contribution dominates, just as one might expect: the starlight from the Milky Way is some two orders of magnitude more intense than the optical flux from distant galaxies.

Only in the microwave region, where the 2.7 K blackbody photon radiation contributes ~ 0.3 eV/cm^3, and in the X-ray region, where there is $\sim 10^{-4}$ eV/cm^3 in hard photons, does the metagalactic contribution greatly exceed the galactic contribution.

Incidentally, this predominance of the metagalactic component demonstrates that ordinary galaxies, with an X-ray luminosity comparable to that of our own galaxy, cannot possibly account for the diffuse X-ray background. After all, out to $z \sim 0.5$, where the most distant galaxies are observed, only a small fraction of the sky (a few percent) is covered by galaxies. In order for galaxies to produce the observed diffuse X-ray flux, one would require the galactic contribution to be ~ 30 times greater than the metagalactic flux, as with starlight.

Of course Figure 2 does not immediately demonstrate that cosmology is as significant for diffuse X-rays as it is for the isotropic microwave photons. One first has to eliminate the possibility that relatively local discrete sources are producing the background radiation. Although we cannot yet be completely sure this is the case, there is some convincing evidence.

First, consider the X-ray emission from normal galaxies. Perhaps with many discrete galactic sources, the X-ray luminosity of our galaxy would be rather higher than one might deduce from the surface brightness in X-rays of the Milky Way. This has been considered by Friedman *et al.* (1967), who have estimated that the 1–10 keV luminosity of our galaxy from discrete sources is $\sim 7 \times 10^{39}$ erg/sec. A more recent estimate (Friedman, 1970) favours a slightly lower value, about a factor of 2 or 3 less. Now the density of galaxies like our own is 0.03 Mpc^{-3} or 10^{-75} cm^{-3}, so that the contribution to the diffuse flux by these galaxies is

$$7 \times 10^{39} \times 10^{-75} \times 4 \times 10^{17} = 2 \times 10^{-6}\,\text{eV cm}^{-3},$$

about a factor of 50 too small to account for the diffuse X-ray flux.

Can more active objects than our galaxy play a role? The data here is still very sparse, but Table I indicates the situation as it presently appears. Some four or so extragalactic X-ray sources have thus far been identified, although of these, only the radio galaxy M87 (Virgo A) has been widely confirmed. The other extragalactic sources for which evidence exists are the Large Magellanic Cloud (Mark *et al.*, 1969), the quasi-stellar radio source 3C 273 (Friedman and Byram, 1967; Bowyer *et al.*, 1970; Friedman, 1970), and the radio galaxy NGC 5128 (Centaurus A) (Bowyer *et al.*, 1970; Byram *et al.*, 1970). In addition upper limits are available for some other objects, in particular for the powerful radio galaxy Cyg A. As is apparent from Table I, none of these objects, if regarded as typical of a class of similar sources, can account for the diffuse X-ray background.

TABLE I

Extra-galactic source luminosities (erg/sec)[a]

	Radio (0.3 mm–30 m)	Visible (1000–10000 Å)	X-ray[b] (1–10 keV)	Space density ($N = 0.03$ Mpc^{-3})
Our galaxy	3×10^{38}	3×10^{43}	$10^{39} - 10^{40}$	N
LMC	10^{36}	5×10^{42}	4×10^{38}	$\sim 10\ N$
M87	1×10^{41}	10^{44}	3×10^{43}	$\sim 10^{-3} N$
Cen A	2×10^{41}		$(1\text{–}5) \times 10^{41}$	$\sim 10^{-3} N$
(NGC 5128)		8×10^{43}		
Cyg A	4×10^{44}	7×10^{44}	$< 10^{43}$	$\sim 10^{-6} N$
3C 273	2×10^{46}	1×10^{46}	1×10^{46}	$\sim 10^{-6} N$

[a] It would be of interest to also be able to compare the luminosities of these sources at infrared wavelengths. However, the only available estimates for luminosities from 1 μ–300 μ are, for the galactic center, 3×10^{41} erg/sec, and for 3C 273, 6×10^{48} erg/sec (Kleinmann and Low, 1970).

[b] The estimates of X-ray source luminosities are from the following sources: our galaxy (Friedman, 1970); LMC (Mark *et al.*, 1969); M87 (Oda and Matsuoka, 1970); Cyg A (Giacconi *et al.*, 1967); Cen A and 3C 273 (Bowyer *et al.*, 1970; Byram *et al.*, 1970; Friedman, 1970).

This situation has been apparent for several years, and it should be clear from the preceding argument, that cosmological effects may well have an important role to play, or else our galaxy may be an unusually weak source of X-rays at the present time. The realization of these possibilities has generated a remarkable flurry of theoretical activity, and this review is devoted to a summary of the significant results that have emerged to further our understanding of the origin of the isotropic X-ray background.

This review is divided into several sections. Sections 2 and 3 discuss the isotropic X-ray background; Sections 4 and 5 are devoted to the isotropic γ-ray background, and a concluding Section 6 discusses future observations and tests of the various theories. A second paper (hereinafter referred to as Paper II) will be devoted to the diffuse galactic X-ray background.

2. Isotropic X-Ray Background: Diffuse Origin

One may roughly categorize the theories of the X-ray background as utilizing either a diffuse origin, in intergalactic space, or a discrete source origin, in remote galaxies. In this section we consider theories which involve a diffuse origin.

A. INVERSE COMPTON MECHANISM

The first theory to gain widespread circulation was based on the inverse Compton mechanism, which involves the scattering of microwave photons by relativistic electrons. This process involves the collision of a fast electron and a low energy photon, with the consequent production of a high-energy recoil photon and a corresponding decrease in the energy of the electron. In the rest-frame of the electron, the interaction is just a classical Compton scattering. In particular, it reduces to Thomson scattering in the limit $\gamma\varepsilon \ll mc^2$, where γ is the Lorentz factor and m the rest mass of the electron, and ε is the initial photon energy. One then obtains for $\gamma \gg 1$,

$$\varepsilon_1 \approx 4\gamma^2\varepsilon/3, \tag{1}$$

where ε_1 is the energy of the scattered photon. The factor $\frac{4}{3}$ appears from the angular integration over an ambient isotropic radiation field, if one assumes the scattered photons to be monoenergetic (Ginzburg and Syrovatskii, 1964). One finds that the lifetime of a relativistic electron against inverse Compton losses is

$$t_c \approx \gamma m_0 c^2/P_c \approx 7 \times 10^{11}\ \mathrm{yr}\,[\gamma w(\mathrm{eV/cm^3})]^{-1}, \tag{2}$$

where w is the energy density of the radiation field. It was soon realized that starlight scattered by cosmic ray electrons in the galactic halo was inadequate to account for the observed X-ray background by about 2 orders of magnitude. However Felten and Morrison (1966) suggested that the cosmic blackbody millivolt radiation, which pervades the Universe, would provide an adequate source of low energy photons in intergalactic space. Note that from Equation (1), in order to produce 10 keV X-rays, we see that ultrarelativistic electrons with $\gamma \sim 3 \times 10^3$ are required. The Compton loss time for an electron with this value of γ is, from Equation (2), $\sim 10^9$ yr, short compared to a Hubble time ($\sim 10^{10}$ yr). Consequently, inverse Compton scattering in intergalactic space is an extremely efficient way of making X-rays: to produce the observed diffuse X-ray flux requires $\sim 10^{-4}$ eV cm^{-3} of ultrarelativistic electrons.

Such a universal energy density of ultrarelativistic cosmic ray electrons is uncomfortably high. Electrons in this energy range are observed indirectly through their synchrotron radiation in radio galaxies. From the observed frequency of radio galaxies, which are commonly giant elliptical galaxies, Schmidt (1966) deduced a harmonic mean lifetime for the radio phase of $\sim 10^9$ yr. If each radio galaxy is assumed to produce over its lifetime $\sim 10^{60}$ erg of relativistic electrons (implying some 10^{62} erg of cosmic rays), then the mean intergalactic relativistic electron density is, if these particles are eventually dumped into space, only about 10^{-5} eV cm^{-3}, or 10^{-3} of the galactic value. It seems difficult to account for an order-of-magnitude more energy in relativistic particles, although recent observations of excess infrared emission from Seyfert galaxies and quasistellar sources pose similar energetic difficulties (Low, 1970).

Cosmology, one might naively suppose, could provide a solution to the energy problem, since the energy density of the microwave radiation increases as* $(1+z)^4$. However, the lifetime of the electrons decreases by just this factor, so there is no net gain (Brecher and Morrison, 1967). Evolutionary effects will help, provided one overcomes the inverse square law, and makes the distant radio galaxies have greater apparent brightness than the nearby sources. In fact recent evidence from the radio source counts and studies of QSS distribution with redshift favour such extremely strong evolution (but see Subsection 3A below).

However a more serious difficulty with the Felten-Morrison theory has arisen as a consequence of the flattening below ~ 40 keV. The average synchrotron spectral index of radio galaxies is 0.7 ± 0.3, with an approximately Gaussian distribution in the dispersion. When ultrarelativistic electrons are injected into intergalactic space, inverse Compton losses dominate the spectrum above ~ 100 MeV, and the photon spectrum steepens by one-half power. (Injection itself produces no change, and Compton losses produce a one-power break, in the electron spectrum.) Consequently, the predicted X-ray spectrum is 1.2 ± 0.3: however it is not possible to account for any asymptotic change in the diffuse X-ray spectrum, as observed at ~ 40 keV. A break is produced in the Felten-Morrison theory, when the inverse Compton loss time exceeds a Hubble time, but this corresponds to a photon energy of < 0.1 keV.

A means of accounting for the flattening at 40 keV has been proposed by Payne (1969), who pointed out that cosmological models exist which are expanding so rapidly that the Compton loss time (2) will decrease with redshift less rapidly than the expansion time, raising the energy at which the break occurs. Unfortunately these models require a value for the cosmological deceleration parameter considerable larger than is consistent with observational evidence (Peach, 1970).

Brecher and Morrison (1969) have suggested an ingenious way out of these difficul-

* Redshift is denoted by z; $z = 0$ describes the present epoch.

ties with the inverse Compton mechanism. These authors argue that ordinary galaxies might provide the electron source. The radio spectra of normal galaxies have been studied by Lang and Terzian (1968) (Figure 3). Although there is a fairly wide dispersion in the radio spectral indices α of normal galaxies, an apparently significant change in slope appears between 500 and 1500 MHz in most of the galaxies observed by Lang and Terzian. The change in radio spectral index amounts to about one-half power, from $\alpha \approx 0.8$ to $\alpha \approx 0.3$. Brecher and Morrison assume that the corresponding electron break is intrinsic to the electron sources in normal galaxies. When these electrons

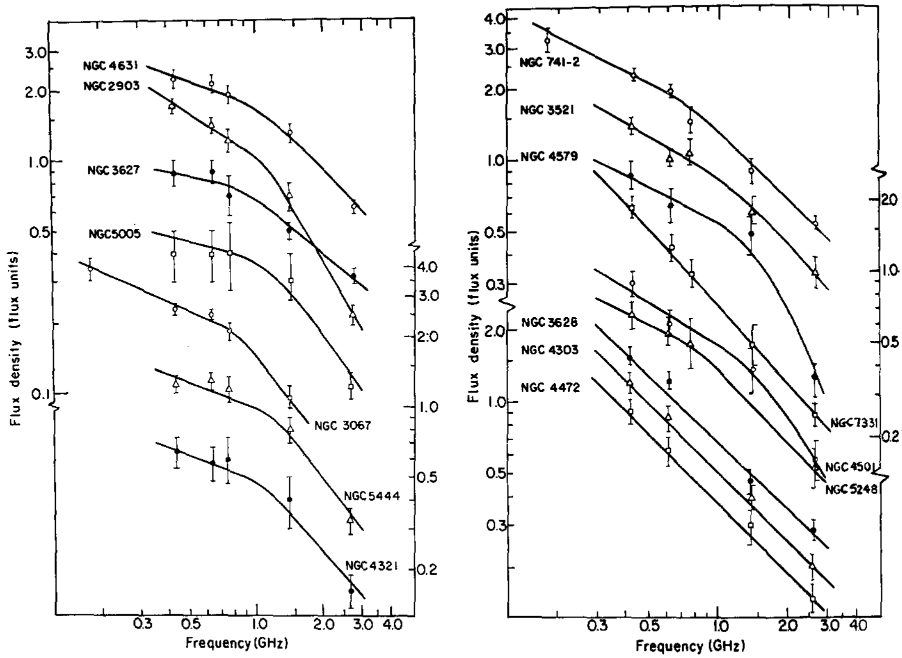

Fig. 3. Radio spectra of normal galaxies (from Lang and Terzian, 1969). The change in slope $\Delta\alpha$ satisfies $\langle\Delta\alpha\rangle \approx 0.8 \pm 0.4$.

diffuse into the intergalactic medium, the electron spectrum is unchanged. A one-power steepening occurs where inverse Compton losses are important, at electron energies above 150 MeV. Consequently, the inverse Compton X-ray spectrum produced has slope ≈ 1.3 above some energy E_b, and slope ≈ 0.8 below E_b, where for a mean galactic field strength of 4×10^{-6}G, E_b is in the range 12 keV–80 keV. The calculated electron spectrum is shown in Figure 4. Note that the dispersion in spectral indices produces a rise at both soft ($\sim\frac{1}{4}$) and hard (~ 1 MeV) photon energies, but that difficulties are encountered in fitting the observations near 1 keV, and also, if the Vette *et al.* (1970) flux is accepted as an isotropic cosmic component, near 6 MeV.

Now if the observed break is produced in the electron sources, the lack of any second break at higher electron energies imposes an upper limit on the galactic lifetime of the trapped electrons of less than a few million years. In fact the energy requirements of the Brecher-Morrison model impose even more severe restrictions on the trapping time. Most normal galaxies are required to produce about 10^{41} erg/sec in GeV electrons: consequently, if the leakage time were $\sim 10^6$ yr, the average cosmic ray density in normal galaxies would exceed that in our own galaxy by an order of magnitude (assuming equal storage volumes, and no halo, but a thick (~ 1 kpc) cosmic ray disc).

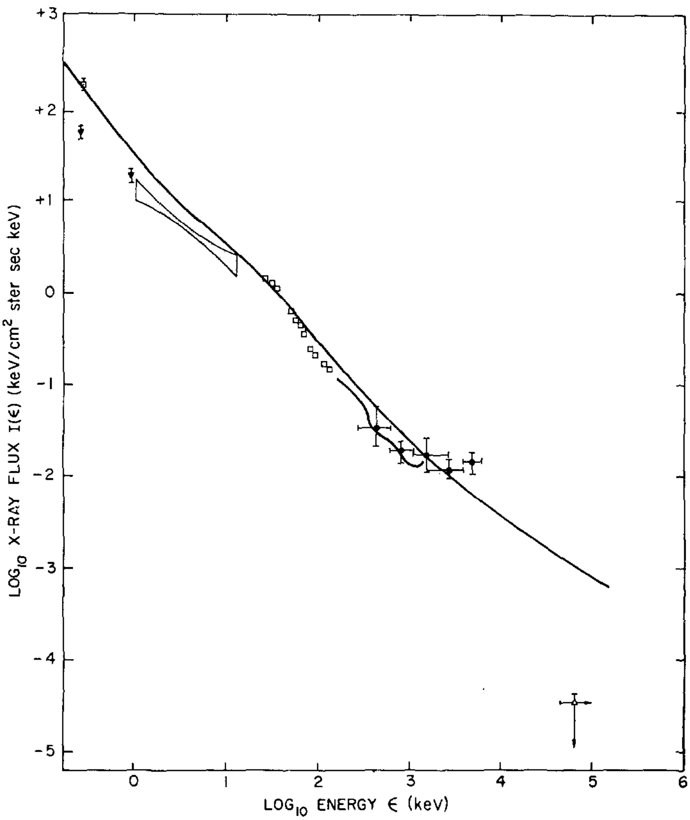

Fig. 4. Theoretical X-ray spectrum calculated by Brecher and Morrison (1969) for inverse Compton X-rays from galactic leakage electrons interacting with the 2.7 K background photons in extragalactic space. The photon spectrum is a power-law in photon energy E with a $\frac{1}{2}$-power break at E_b, and multiplied by a factor exp $\{\frac{1}{2}[\mu \ln(E/E_b)]^2\}$. The dispersion in spectral indices μ is set equal to 0.3, and the photon break (corresponding to $\Delta\alpha = \frac{1}{2}$) is chosen at $E_b = 40$ keV. Some representative observations are also shown (legend as Figure 1).

Equipartition arguments do indeed yield such a high energy density, for a magnetic field of a few μG, provided one assumes a uniform distribution of cosmic ray electrons. In our own galaxy, however, direct measurements of cosmic ray electrons are available, and even if one assumes the nonexistence of a halo, the trapping time for cosmic ray electrons in the disc is required to be $\sim 10^5$ yr. Cosmic ray protons, by virtue of their high degree of observed isotropy, must have a lifetime in the galaxy exceeding 10^7 yr. All theories of cosmic ray diffusion predict similar containment times for electrons and protons. By some unspecified means, the Brecher-Morrison (1969) theory requires very different histories of cosmic ray protons and electrons, yet their source spectra must be similar. An interesting alternative is suggested by Brecher (1970), who argues on the basis of a study of radio, infrared and X- and γ-ray emission from the Galactic Centre that galactic nuclei may be the source of the metagalactic cosmic ray electrons. Only a small fraction of the power produced in the nuclei would diffuse into the disc, thus avoiding the galactic lifetime difficulty.

Note that all the preceding theories, which require injection of ultrarelativistic electrons into intergalactic space, take no account of possible adiabatic losses. Although the electron spectrum would not be affected, these losses may greatly increase the energy requirements.

B. THERMAL BREMSSTRAHLUNG

Is there an intergalactic gas? It seems hard to believe that the process of galaxy formation would have been so efficient as to leave nothing behind. A reasonable assumption might to be to assume that there is about as much matter in gaseous form in between the galaxies, as there actually is in the galaxies themselves. If we adopt a Hubble constant of 75 km $\sec^{-1}$ Mpc^{-1} (Sandage, 1968), the mean mass density due to galaxies is 1.4×10^{-31} g cm^{-3} (Shapiro, 1970), whence the mean particle density $n_0 = 8 \times 10^{-8}$ cm^{-3}. If there is a lot of 'missing matter' (for example, to bind clusters of galaxies and to close the Universe itself) n_0 may be rather larger. The critical value for closure $n_0 = 3\mathrm{H}_0^2/8\pi\mathrm{G} = 7 \times 10^{-6}$ cm^{-3}. The intergalactic matter must be very highly ionized, since the neutral density at $z=2$ cannot exceed 10^{-11} cm^{-3} [from the lack of Ly-α absorption in the quasi-stellar source 3C9 (Gunn and Peterson, 1967)]. One is therefore led to consider the possibility of observing the thermal radiation.

A temperature of 10^9 K was originally predicted for the intergalactic medium (IGM) by Gold and Hoyle (1958) on the basis of their steady state cosmology. Gould and Burbidge (1963) pointed out that the early observations of diffuse X-rays set a limit of 10^7 K on the temperature of a dense uniform intergalactic plasma. The discovery of a diffuse flux at $\frac{1}{4}$ keV, that has necessarily to originate outside the neutral hydrogen disc of our galaxy by virtue of its observed increase in intensity with increasing galactic latitude, has renewed interest in free-free radiation as an emission mechanism. The free-free emission from a uniform hydrogen plasma of electron density n_0 and radius R may be conveniently written in the form (Allen 1963)

$$J_\nu \approx 800\,\bar{g}\,(R/10^{28}\ \mathrm{cm})\,(n_e/10^{-5}\ \mathrm{cm}^{-3})^2 \exp(-h\nu/kT) \times T_6^{-1/2}\ \mathrm{keV}(\mathrm{cm}^2\ \mathrm{sec\ ster\ keV})^{-1} \qquad (3)$$

where $T_6 = T/10^6$ K and $\bar{g}$ is the velocity-averaged Gaunt factor. Hence the measured flux corresponds to an emission measure $n_e^2\,R \sim 0.1$ cm^{-6} pc, if $T \approx 10^6$ K. In fact, to compare the predicted spectrum of soft X-rays with the observations, account must be taken of thermal emission from earlier epochs, when the universe was denser and, possibly, hotter. Following the early work of Field and Henry (1964) and Weymann (1967), Bergeron (1969) has recently recalculated the thermal emission from a uniform

IGM, assuming a sudden heat input at a redshift of about 3. Some of her results are shown in Figure 5. An important constraint on Bergeron's models is that the IGM be highly ionized at $z \sim 2$ in order to account for the lack of Ly-α absorption in the spectrum of 3C9, The observations of X-rays at $\frac{1}{4}$ keV and near 1 keV allow as possible models:

(a) emission from a dense IGM ($n_0 = 10^{-5}$ cm^{-3}, $q_0 = 1$) at a present temperature of about 10^6 K if we use the high value for the $\frac{1}{4}$ keV flux reported by Henry *et al.* (1968) (with a factor ~ 3 correction for interstellar absorption); or

(b) emission from a uniform medium of density 3×10^{-6} cm^{-3} ($q_0 = 0.2$) at 2.5×10^6 K if we use the lower $\frac{1}{4}$ keV fluxes found by the Berkeley and Wisconsin groups (in this case with only a small correction for interstellar absorption).

Note that observations at ~ 1 keV are an important constraint in setting an upper limit on the gas temperature at present. The observations at 0.25 keV set interesting theoretical limits on the earliest epoch at which the heating of the IGM can occur. If

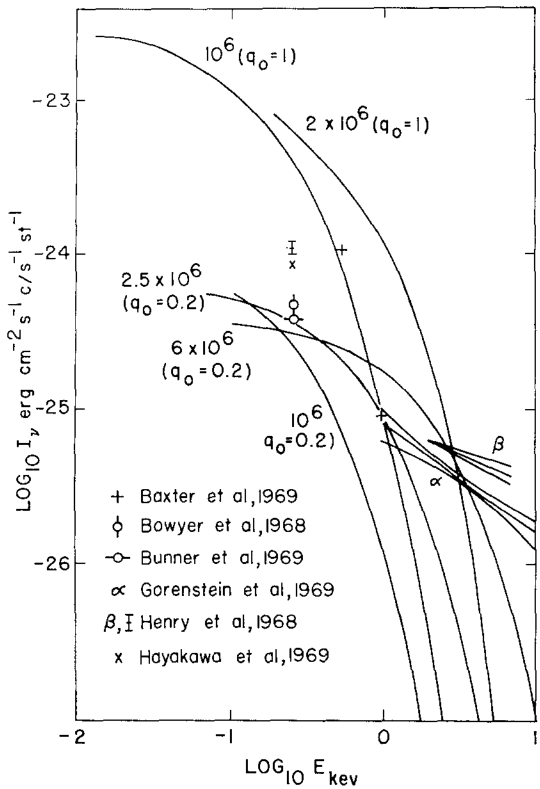

Fig. 5. Thermal bremsstrahlung from a dense hot intergalactic plasma (after Bergeron, 1969). Spectra are shown for the case in which sudden heating of the IGM occurs at $z = 3$, and which satisfy the constraint posed by the absence of Ly-α absorption in quasi-stellar source spectra. The calculations shown are for $q_0 = 1$ and $q_0 = 0.2$ cosmological models, and the values of the temperature T at $z = 0$ are also indicated. Some observations of low energy isotropic X-radiation, uncorrected for interstellar absorption, are also shown.

this epoch corresponds to a redshift z_i, then the present temperature of the IGM $T(z=0) \gtrsim T(z_i)\,(1+z_i)^{-2}$. The equality sign corresponds to sudden heating at z_i, with adiabatic cooling thereafter. Some results of a detailed calculation of the heating of the IGM are shown in Figure 6, which indicates the allowed range of z_i in a $q_0 = 1$ model, for different values of J(0.27 keV) (Bergeron, 1970). An upper limit of either $\tau = 0.4$ or $\tau = 0.1$ is assumed for the Ly-α optical depth in the emission spectrum of 3C9 at $z \approx 2$. Hence the existence of a uniform dense IGM ($n_0 \approx 10^{-5}$ cm^{-3}) at $T(z=0) \approx (1\text{–}3) \times 10^6$ K is consistent with the soft X-ray observations provided, for example, that $z_i \lesssim 13.5$ for J(0.27 keV) = 450 keV/cm^2 sec ster keV or $z_i \lesssim 7$ for J(0.27 keV) = 40 keV/cm^2 sec ster keV.

Incidentally, lowering the Hubble constant to 50 km/sec/Mpc, as has recently been advocated (Abell and Eastmond, 1970), reduces the closure value of n_0 to $\sim 3 \times 10^{-6}$ cm^{-3} (but note that the X-ray emission varies as H_0^3 for a given value of q_0).

If the IGM is nonuniform, however, the mean density required to account for the $\frac{1}{4}$ keV flux by free-free emission is considerably reduced. Suppose, for example, that the average gas density follows the distribution of galaxies. Limber (1954), in a study of the distribution of galaxies on the sky, found that the mean square number density of galaxies is some twenty-five times greater than the square of the mean. Then the

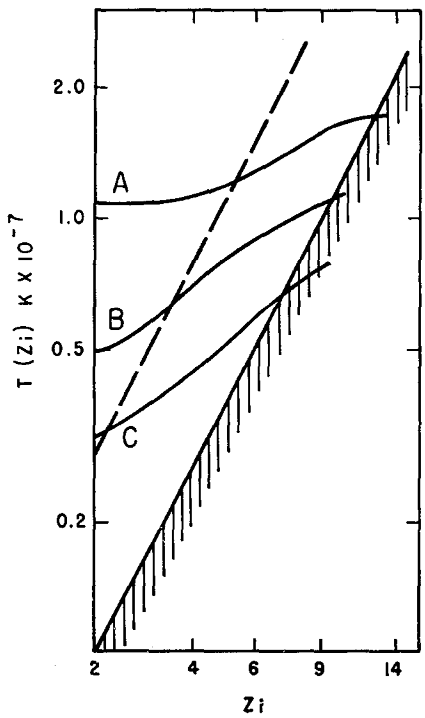

Fig. 6. Temperature of the intergalactic gas at the redshift z_i at which the heating occurs plotted versus z_i, for different values of the soft X-ray flux. Curve A: J(0.27 keV) = 450 keV/cm^2 sec ster keV; Curve B: J(0.27 keV) = 150 keV/cm^2 sec ster keV; Curve C: J(0.27 keV) = 40 keV/cm^2 sec ster keV. Initial temperatures falling above the hatched line correspond to a Lyman alpha optical depth $\tau = 0.4$ in the spectrum of 3C9; the dashed line corresponds to $\tau = 0.1$.

required mean gas density would be reduced to $\langle n_0 \rangle \approx (10^{-6} - 3\times10^{-6})$ cm^{-3}. More gas might be available in clusters of galaxies, in an intra-cluster medium: this could plausibly reduce $\langle n_0 \rangle$ by a factor of ~ 10 over its value in the uniform case. Incidentally, if gas in clusters contributes to the $\frac{1}{4}$ keV flux, one would expect a harder thermal component in addition to that at 10^6 K. Rich clusters of galaxies would necessarily heat up any intra-cluster gas to a temperature of $\sim$1–10 keV, corresponding to random motions of 300–1000 km/sec, otherwise the gas would fall in the potential well to the centre of the cluster.

It may not even be necessary to seek an intergalactic mechanism for free-free emission. Since an emission measure of only $n_e^2 R \sim 0.1$ cm^{-6} pc is required for gas at 10^6 K, one could equally well consider a hot galactic halo ($R = 10^4$ pc, $n_e = 3\times10^{-3}$ cm^{-3}), or matter in between the galaxies of the Local Group ($R = 10^6$ pc, $n_e = 3\times10^{-4}$ cm^{-3}) (cf. Rees *et al.*, 1968). Measurements of the angular isotropy at high galactic latitudes of the $\frac{1}{4}$ keV flux are needed in order to decide between these possibilities.*

Sunyaev (1969) has argued that the low H I column densities found for the H I isophotes at the periphery of M31 are incompatible with the Lyman continuum flux implied by a hot plasma at the critical density: that is, the H I would be ionized by this radiation. On the other hand, Felten and Bergeron (1969) have pointed out that it is possible to shield the H I disc at 25 kpc from the centre of M31 by a surrounding H II slab, with emission measure ~ 0.1 cm^{-6} pc. Clearly, this argument must be qualitatively correct: eventually a steady state will be produced with recombinations behind the ionizing front balancing the ionizations. The only question remaining is whether such a slab (thickness, say, a few kpc; density $\sim 10^{-2}$ cm^{-3}) is consistent with observational data.

In fact there are at least three lines of evidence that point to the existence of H II around the disc, that extends considerably further from the plane than does most of the H I. The relevant observations are:

(a) the dispersion measures of some high latitude pulsars, which provide a measure of $n_e l$ (where l is the line-of-sight distance), and are larger than can easily be explained with the same average electron density deduced from dispersion measures of pulsars in the galactic plane (Rohlfs *et al.*, 1969);

(b) data on low frequency radio-wave absorption of galactic and extra-galactic discrete sources, and also of the galactic nonthermal radio background radiation (free-free absorption yields a measure of $n_e^2 l T^{-3/2}$), which indicate a half-thickness for the absorbing layers of ~ 500 pc (Bridle and Venugopal, 1969); and

(c) the extremely strong interstellar H and K lines of Ca II observed in the spectra of blue stars in some distant globular clusters (Greenstein, 1968). The equivalent widths are a measure of $n_e n_H l T^{-1/2}$, and could be explained if the line-of-sight through the galactic H II distribution were rather higher than predicted from the neutral hydrogen distribution: moreover, for a given line-of-sight, raising the electron density increases the fraction of Ca in the form of Ca^+ (and so raises the abundance).

* The ideal energy for carrying out such an experiment would be at ~ 0.5 keV, since the effects of interstellar absorption would then be negligible at high latitudes.

Even if the H II indicated by these observations fails to be an adequate shield of a uniform H I slab, one could always put the H I in clouds. Normal H I clouds are opaque to photons below about $\frac{1}{4}$ keV; the harder photons would simply heat and partially ionize the cloud, maintaining it in pressure equilibirum with the surrounding low density ionized hydrogen (Silk and Werner, 1969).

C. NONTHERMAL PROTON BREMSSTRAHLUNG

If the thermal bremsstrahlung interpretation of the $\frac{1}{4}$ keV excess is correct, one is left with a severe theoretical problem, concerning the heat source of the gas. Fortunately the cooling time at present is longer than a Hubble time, so one can argue that the gas was heated instantaneously, at some past epoch. Several authors have suggested that low energy cosmic rays are responsible for the heating of the gas (Sciama, 1964; Ginzburg and Ozernoi, 1966; Gould and Ramsay, 1966). Indeed, it is difficult to think of an alternative mechanism (photoionization would, for example, result in too low a temperature for appreciable X-radiation to be produced). The energy density that must be supplied to the IGM to maintain $n_0 \approx 10^{-5}$ cm^{-3} at 10^6 K or 100 eV per particle is $\sim 10^{-3}$ eV/cm^3. Since a fast electron or proton of energy*

$$E_c \approx 0.8(M/m)^{1/3}[(n_0/10^{-5})(75/H_0]^{2/3} \text{ MeV} \tag{4}$$

(≈ 10 MeV for a proton or 0.8 MeV for an electron, with $n = 10^{-5}$ cm^{-3}) is stopped within a Hubble time, we see that $\sim 10^{-3}$ eV/cm^3 in 10 MeV protons are required (and correspondingly more cosmic rays if the mean energy exceeds 10 MeV).

In fact low energy cosmic rays will not only heat the gas, but a small fraction of their energy will be radiated away, as nonthermal bremsstrahlung, when the fast protons interact with thermal electrons. The efficiency at which a nonrelativistic cosmic ray radiates bremsstrahlung is (Jackson, 1968)

$$\frac{\Delta E^{\text{brem}}}{\Delta E^{\text{coll}}} \approx \frac{4}{3\pi}\,\alpha \left(\frac{v}{c}\right)^2 \frac{1}{B} \tag{5}$$

where $\alpha = \frac{1}{137}$, v is the particle velocity, and $B \approx 38.7 + \ln E/mc^2 - \frac{1}{2}\ln n$. Now the bremsstrahlung cross-section is

$$\sigma_b = \frac{2\pi}{3}\,\alpha\sigma_T \left(\frac{c}{v}\right)^2 G, \tag{6}$$

where $\alpha = \frac{1}{137}$, σ_T is the Thomson cross-section, and G is the Gaunt factor defined by Bekefi (1966), with a logarithmic dependence on particle energy. The corresponding emissivity of nonthermal bremsstrahlung from a particle spectrum J(cm^{-2} sec^{-1} ster^{-1} keV^{-1}) interacting with an ionized medium of density n(cm^{-3}) is

$$j_\varepsilon = n \int_\varepsilon^\infty \mathrm{d}E\, J\, \sigma_b \text{ keV cm}^{-3}\text{ sec}^{-1}\text{ ster}^{-1}\text{ keV}^{-1} \tag{7}$$

Hence the spectrum of nonthermal bremsstrahlung, for a power-law cosmic ray spectrum, has approximately the same slope in energy units for nonrelativistic particles.

* In this expression M denotes the proton mass and m the mass of an electron.

[Fast proton bremsstrahlung resembles ordinary electron bremsstrahlung, in the centre-of-momentum frame of the system, in which the proton is approximately at rest.] Hence, for a spectrum of negative slope, cosmic rays of energy $\sim E$ produce photons of energy $\sim E(m/M)$. Less than 1 part in 10^4 of the energy in fast protons is radiated away.

At relativistic energies, a qualitative difference emerges between non thermal electron and proton bremsstrahlung. The spectrum of electron bremsstrahlung flattens by one-power of energy at high energies, since the cross-section is similar to (6). However the asymptotic form of the proton bremsstrahlung cross-section is a steep function of proton energy, varying as E^{-3} and so the corresponding spectrum steepens by two powers of energy at high energies.

Several applications of this mechanism have been made, following the original suggestion by Hayakawa and Matsuoka (1964). Boldt and Serlemitsos (1969) proposed that the diffuse X-ray background might be due to proton bremsstrahlung in the IGM. More recently, Brown (1970) has suggested that the 0.25 keV flux may be suprathermal proton bremsstrahlung, in the galactic halo, or further afield. The enormous inefficiency of this mechanism requires a huge output of protons. For example, if the $\frac{1}{4}$ keV flux is produced in the halo, the X-ray power involved is about 10^{42} erg/sec. Consequently, with a containment time of 10^8 yr in the halo, the galaxy would have to be producing MeV protons at a rate exceeding its optical luminosity. This is some two orders of magnitude more energy than is available from Type I supernovae, one of the likely sources of suprathermal particles. Proton bremsstrahlung in the intergalactic medium runs into another difficulty. Most of the energy is channelled into thermal radiation. With $n = 10^{-5}\ \mathrm{cm}^{-3}$, the density of low energy protons ($E \sim 10$ MeV) cannot exceed $10^{-3}\ \mathrm{eV\ cm}^3$, and the nonthermal bremsstrahlung X-rays can amount to only $\sim 10^{-7}\ \mathrm{eV/cm}^3$, while the thermal bremsstrahlung produced is $\sim 10^{-4}\ \mathrm{eV/cm}^3$.

In an attempt to account for the diffuse X-rays from 1 keV–1 MeV, Hayakawa (1969a, b) has utilized evolutionary effects to augment the density of low energy cosmic rays at early epochs in the Universe. These cosmic rays, he argues, are produced by radio galaxies whose number density appears to rise steeply at redshifts of 2 or more in order to account for the $\log N - \log S$ graph of radio sources. In addition, the gas density increases, so one can obtain a drastic increase in bremsstrahlung efficiency by going back to large redshifts. In order to avoid excessive thermal radiation, it turns out that one has to go to $z \gtrsim 30$ in this model (Silk, 1970). It is possible to produce a flattening below 5 keV in the photon spectrum, where the cosmic rays (near ~ 10 MeV) are stopped by ionization losses.* This effect is similar to that discussed below for cosmic ray electrons.

* I am indebted to Dr. E. Boldt for drawing my attention to the fact that Hayakawa (1969b) has overestimated the photon energy at which flattening occurs, owing to an apparent confusion with the related process, proton inner-bremsstrahlung, which occurs when a proton of kinetic energy E interacts with inner-shell electrons to produce knock-on electrons of maximum energy $4\ Em/M$. The characteristic photon energy is therefore a factor 4 greater than in the proton bremsstrahlung process, which occurs when fast protons interact with free electrons, or with bound electrons whose binding energy is small compared to the proton kinetic energy.

D. NONTHERMAL ELECTRON BREMSSTRAHLUNG

One may gain a useful factor by considering the nonthermal bremsstrahlung of cosmic ray electrons. If the ratio of energy densities in electrons to protons is 1:100, one obtains an order of magnitude more bremsstrahlung radiation from the electrons than from the protons. In fact, in the Crab nebula, the ratio of cosmic ray electrons to protons is of order unity (Shklovsky, 1968). An argument given below indicates that a similar ratio may also be appropriate for low energy cosmic rays in the IGM.

The non-thermal electron bremsstrahlung process was suggested as a possible mechanism for diffuse X-ray production by Silk and McCray (1969). Much of the preceding discussion for nonthermal proton bremsstrahlung is applicable to electron bremsstrahlung provided that one sets $m/M=1$ in equation (4). Despite the increased efficiency, bremsstrahlung is not an important energy loss for electrons in the IGM. At $E<E_c$, ionization losses dominate, and at higher energies adiabatic expansion provides the main form of energy loss until inverse Compton losses become significant. Since bremsstrahlung is always inefficient as an energy loss for electrons, one can utilize the cosmological expansion to greatly boost the net radiation by considering contributions from earlier epochs.

The transfer equation for cosmic ray electrons propagating in a uniform field-free IGM must first be solved. Analytic and numerical solutions of the time-dependent diffusion equation have been obtained by Arons, McCray and Silk (1971; subsequently denoted by AMS).

The diffusion equation is

$$\frac{\partial N_e}{\partial t} + \frac{\partial}{\partial E}\left[b(E,t)\,N_e\right] = q(E,t), \tag{8}$$

where $N_e(E,t)\,\mathrm{d}E d^3x=$ number of electrons with energy between E and $E+\mathrm{d}E$ in the co-moving volume element d^3x (Kardashev, 1962). The loss term $b(E,t)$ is written as

$$b(E,t) = b_{\text{coul}} + b_{\text{exp}} + b_{\text{comp}},$$

and expressions for the Coulomb losses b_{coul}, adiabatic expansion losses b_{exp}, and inverse Compton losses b_{comp} are given by AMS. Injection of a simple powerlaw spectrum was assumed, and two modes of injection for $q(E,t)$ were considered: (a) burst injection, over a time short compared to the cosmic expansion time-scale, and (b) continuous injection of the same power-law spectrum over times long compared to the expansion time. Mode (a) is approximated by writing

$$q = N_e(E,t)\,\delta(t-t_i) \tag{9}$$

and mode (b) by writing

$$q = q_0 E^{-\gamma} f(t), \tag{10}$$

where $f(t)$ may be taken, in a simple model, to have an exponential or a power-law dependence on t. Analysis of both the radio source counts (Longair, 1966; Doroshkevitch *et al.*, 1969) and of the distribution of quasi-stellar sources with redshift (Schmidt, 1968; Petrosian, 1970) indicates a rapid evolution of source number density and/or luminosity with cosmological epoch, and provides a basis for the assumption about the form of $f(t)$. Some of the numerical solutions obtained for the relaxation of cosmic ray electron spectra in a uniform and isotropically expanding IGM are shown in Figures 7, 8, and 9.*

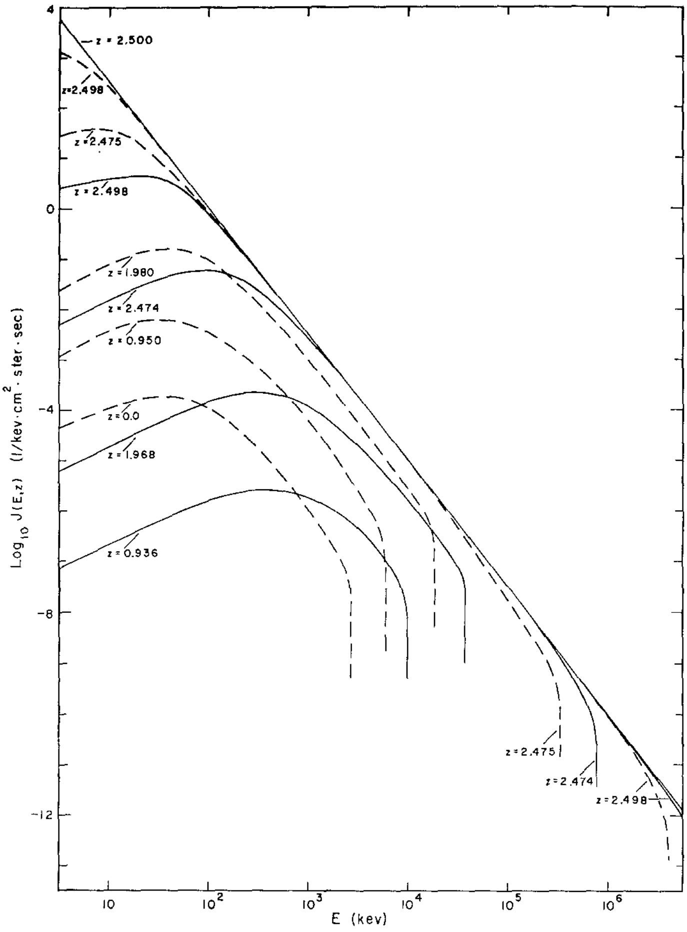

Fig. 7. Relaxation of cosmic ray electron spectrum in intergalactic space (Arons *et al.*, 1970). Numerical solution for burst injection at $z = 2.5$ of a power law (in energy) electron spectrum, with spectral index 2.5. Solid curves: $n_0 = 10^{-5}$ cm^{-3}. Dashed curves: $n_0 = 10^{-7}$ cm^{-3}. In the $n_0 = 10^{-5}$ cm^{-3} case, the spectrum is completely depleted by Coulomb losses before the present epoch is reached. The amplitudes of the spectra in Figures 7–9 are all normalized to the same arbitrary scale.

* In Figures 7–9, and the remainder of this section, the cosmic ray electrons are described in terms of their specific intensity relative to the reference frame at $z = 0$, defined by

$$J_e(E, z) = N_e\,[E, t(z)]\; v\,(E)\,(1 + z)^3/4\pi$$

cm^{-2} sec^{-1} ster^{-1} keV^{-1}

Figure 7 shows the relaxation of a burst of electrons injected at $z=2.5$. The electron spectral index is 2.5. Note that Coulomb losses flatten the low energy electrons, to give an asymptotic slope of $+\frac{1}{2}$. This break depends mostly on n_0, and varies from 60 to 800 keV at $z=0$, for $n_0=10^{-7}$ to $10^{-5}\ \mathrm{cm}^{-3}$. At high energies inverse Compton losses completely cut off the spectrum above a critical energy. Even electrons with infinite energy lose all their energy in a finite time. The Compton cut-off is at about 10 MeV for $z=2.5$ [and depends on z as about $(1+z)^{-2}$]. Something at first sight quite surprising occurs when the electron spectral index $\gamma<2$. Here one has infinite energy in the spectrum (if continued to arbitrary energy), and so one has an upturn at the Compton cut-off, where the electrons are piling up (Figure 8). Exactly the same phenom-

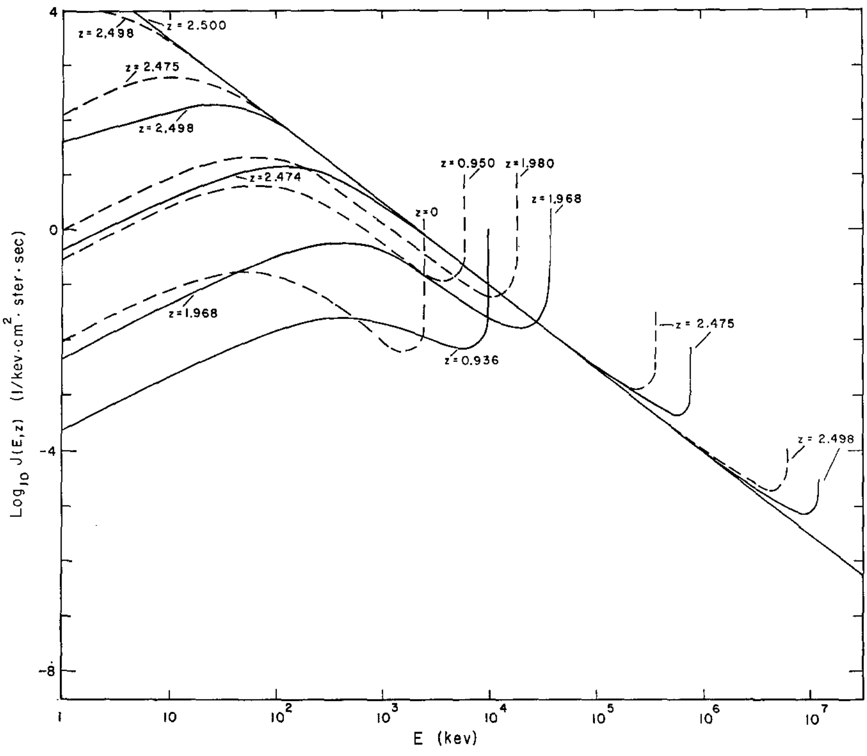

Fig. 8. Same as Figure 6, except $\gamma=1.5$.

enon occurs in the relaxation of synchrotron spectra in expanding radio sources (Kardashev, 1962). Finally, Figure 9 shows the case of continuous injection. Here one has a low energy flattening by $\frac{3}{2}$ power in spectral index due to Coulomb losses, and a steepening by one power of energy at high energies (as found in the simple equilibrium calculations). The relaxation of the ultrarelativistic electron spectra has also been studied independently in a recent paper by Rosental and Shukalov (1969), with application to inverse Compton X-radiation. To calculate the net flux of non-thermal bremsstrahlung radiation, one must perform an integration over redshift.

In general, for any mechanism or source distribution, one proceeds as follows.

Given the emissivity of radiation per unit volume, one may write the resultant energy flux, integrated over intergalactic space, as

$$J(\varepsilon_0)\,\mathrm{d}\varepsilon_0 = \int j(\varepsilon)\,\frac{\mathrm{d}\varepsilon\,\mathrm{d}V}{4\pi r_L^2},$$

where $\mathrm{d}V$ is the spatial volume element in co-moving coordinates, ε is the energy of a photon at emission, and $\varepsilon_0 = \varepsilon(1+z)^{-1}$ its energy in the observer's rest frame. In this integral, the background radiation is regarded as the sum of flux contributions from the concentric, co-moving spheres $r = r_L$, the luminosity distance to any given sphere.

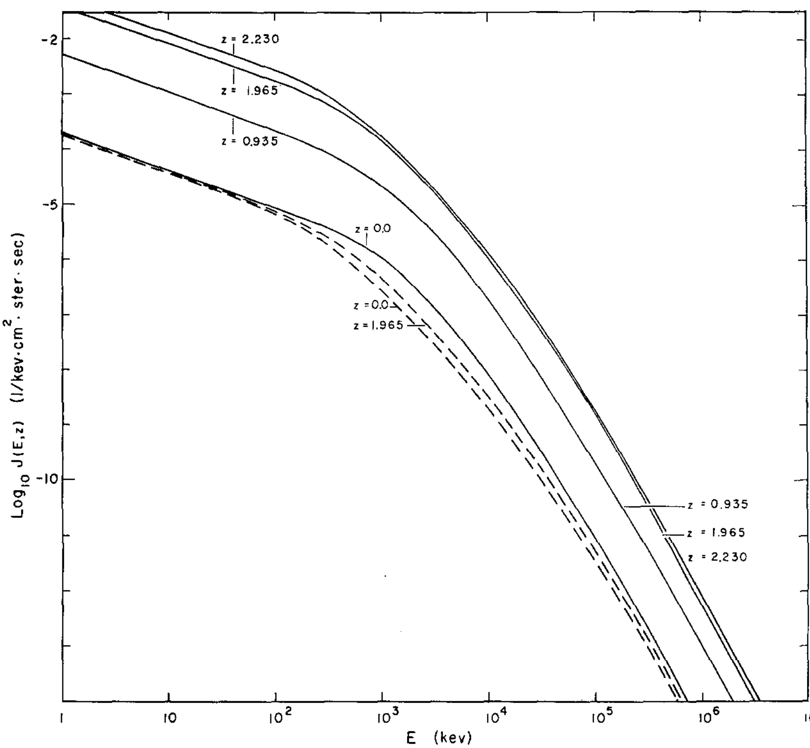

Fig. 9. Numerical solution for continuous injection of electrons with source function $q(E,z) = q_0(1+z)^p E^{-\gamma}$ for z 2.5. Here $\gamma = 2.5$ and $n_0 = 10^{-5}\ \mathrm{cm}^{-3}$. Solid curves: $p = 5$. Dashed curves: $p = 0$.

Since $r_L = r(1+z)$ (McVittie, 1965), one obtains the result, for radial null geodesics in a Friedmann universe, that

$$J(\varepsilon_0)\,\mathrm{d}\varepsilon_0 = \frac{c\,\mathrm{d}\varepsilon_0}{4\pi H_0}\int_0^z \frac{j[\varepsilon_0(1+z)]}{(1+z)^3}\left(H_0\,\frac{\mathrm{d}t}{\mathrm{d}z}\right)\mathrm{d}z\ \mathrm{keV}(\mathrm{cm}^2\ \mathrm{sec\ ster\ keV})^{-1},$$

where the function $H_0\mathrm{d}t/\mathrm{d}z$ is specified by choice of the deceleration parameter q_0, e.g. $H_0\ \mathrm{d}t/\mathrm{d}z = (1+z)^{-2.5}$ if $q_0 = \frac{1}{2}$, and $H_0\ \mathrm{d}t/\mathrm{d}z \approx (1+z)^{-2}$ if $q_0 \ll 1$.

A nonrelativistic calculation of nonthermal bremsstrahlung radiation, with burst injection of electrons, has been published by Silk and McCray (1969). It was found necessary to use a low density IGM to get the cosmic ray electrons to break at low enough energy to give $E_b \sim 40$ keV; this of course reduced the efficiency of the mechanism. We suggested that a burst of cosmic rays injected at $z \sim 10$ would relax to give a spectrum that fitted the data adequately above E_b; however below 10 keV, the burst model gave too flat a photon spectrum.

At relativistic energies, the efficiency of electron bremsstrahlung increases, and equation (5) should be replaced by

$$\frac{\Delta E^{\text{brem}}}{\Delta E^{\text{coll}}} = \frac{4}{3\pi} \alpha \gamma \frac{\ln 192}{B}. \tag{11}$$

In fact the asymptotic expressions derived by AMS are amenable to a straight-forward analytic discussion of the nonthermal bremsstrahlung X-radiation, and the

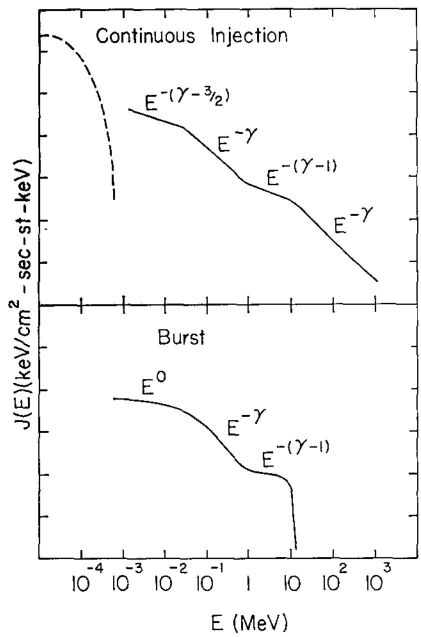

Fig. 10. Nonthermal bremsstrahlung X-radiation from cosmic ray electrons in intergalactic space for burst injection and for continuous injection models. These spectra are only qualitative, and intended to illustrate the significant features of the X-ray spectrum.

qualitative features that emerge from this study are shown in Figure 10. Note that at nonrelativistic electron energies, the bremsstrahlung energy spectrum is similar to the electron spectrum, while at relativistic energies a flattening occurs above 1 MeV because of the piling-up of electrons degraded by Compton losses, and also in part due to the natural one-power flattening of the radiation spectrum.

By a suitable combination of burst and continuous injection spectra it seems clear that one can reproduce both the 40 keV break and the 1 MeV excess in the observed diffuse X-ray spectrum. The energy requirements of this model are quite moderate: from the electron spectra in Figures 7–9, it is apparent that even injection at $z=2.5$ gives one an enhancement of some two or three orders of magnitude in the electron flux, for a given flux at $z=0$. This indicates that in order to produce the observed X-ray background, up to 10^{-3} eV/cm^3 of low energy electrons must be presently in the IGM, with injection having occurred at $z\sim 3$ (Silk, 1970).

An interesting mechanism for producing suprathermal electrons has been recently suggested by Pikelner and Tsytovich (1969). Although these authors were interested in the interstellar medium, their results are extremely relevant for the IGM. It is shown that low energy protons lose most of their energy in low density ionized regions by plasma wave production. These waves are Landau-damped, and simultaneously accelerate thermal electrons. This mechanism is extremely efficient: if the protons are completely stopped, all their energy goes into the thermal plasma via the production of suprathermal electrons. One ends up with approximate equipartition between ionization losses by cosmic rays and the energy in suprathermal electrons. The equilibrium electron spectrum is fairly insensitive to the slope of the cosmic ray spectrum, and is very approximately $\propto E^{-1}$ in the region where ionization and Compton losses are unimportant.

Thus in this picture, the ionization and heating of the IGM is achieved by low energy cosmic ray protons injected by radio galaxies and QSO's at $z\sim 3$, these sub-cosmic rays producing suprathermal electrons in profusion.

3. Isotropic X-Ray Background: Discrete Source Origin

A. NORMAL GALAXIES

As has been pointed out in the introductory section, normal galaxies, if assumed to emit X-rays at the same rate as our own galaxy, fail by 1 to 2 orders of magnitude to account for the diffuse X-ray background above 1 keV.

The situation with the $\frac{1}{4}$ keV flux is similar, since interstellar absorption is only important at distances greater than ~ 100 pc, where the contribution from discrete sources in the galaxy would only enter logarithmically into the intensity of the galactic diffuse component.

Two ways around this difficulty have been proposed. In one version, evolution of the X-ray power of normal galaxies with redshift is postulated (Silk, 1968). Clearly, one accounts for any observed flux by postulating enough evolution. One constraint is that the radio power cannot evolve in the same way without violating the observed limit on the extragalactic radio background. Agreement with the spectrum of the diffuse component in a model of evolving galactic X-ray sources is easily attained only in the energy range 1–4 keV, where Sco X-1-type sources are dominant (Fujimoto *et al.*, 1969).

Quasars do show strong evidence for an increase in coordinate number density (relative to the expansion of the universe). Schmidt (1968) finds at $z=2$, a density enhancement over the local value by some two or three orders of magnitude. If, in addition, one assumes that all radio-quiet QSS possess a similar rapid evolution, one can just fit the observed flux by $z=3$ if 3C 273 has an X-ray luminosity typical of all QSS. As far as radio galaxies are concerned, one can explain the diffuse X-rays using these objects, provided that the strong evolution found in radio luminosity is assumed to continue out to greater redshifts for the X-ray emission, or else the X-ray luminosity must evolve more strongly than the radio luminosity, in order not to produce excessive radio background (Silk, 1969).

This type of approach seems to raise more questions than it solves. One should perhaps abandon it, at least until the X-ray luminosities and spectra of a few QSS or radio galaxies are measured, or in the case of normal galaxies, until a better theoretical understanding of their evolution is achieved.

A somewhat different approach was suggested by Shklovsky (1969), who pointed out that supernova shells in normal galaxies may be prolific emitters of X-rays over a relatively short period of time (perhaps 10^5 yr), as they interact and heat the surrounding interstellar gas. Most of the kinetic energy of the shell has to be radiated away. Now the cooling curve peaks at $\sim 10^6$ K, and a considerable part of the emission is in O^{+7} and O^{+6} lines at ~ 20 Å. One can account for the $\frac{1}{4}$ keV flux in this manner, provided one assumes the galaxies to be present at a redshift of ~ 1. An interesting prediction of this model is that our galaxy should have a diffuse component from supernova shells at ~ 20 Å. This is discussed quantitatively in Paper II.

Still another possibility has been recently proposed by Apparao (1970), Tucker (1970) and Werner *et al.* (1970). It is speculated that a supernova may emit prolifically in X-rays for a brief period following the explosion. Theoretical studies of pulsars suggest that much of the early luminosity (for less than 1 yr) may be in hard photons. Such radiation would not be seen at present, unless a supernova has exploded in the galaxy within a year, but could conceivably account for the entire diffuse X-ray background. The problem with this hypothesis is that one has no theoretical clue at present as to the spectrum predicted for the X-ray burst. Since the spectrum of the diffuse X-ray background and the intensity must both be accounted for in any satisfactory theory, one has to conclude that such speculations are premature.

B. INVERSE COMPTON RADIATION FROM RADIO GALAXIES

Inverse Compton scattering of microwave photons also occurs in the extragalactic radio sources. The condition that the inverse Compton drain on the relativistic electrons exceeds the synchrotron losses by a sufficient margin (roughly 1000:1) to avoid exceeding the limits on extragalactic radio background radiation requires that the average magnetic field be less than about 2×10^{-8} G (Kawabata *et al.*, 1969). Such low fields are untenable even in the extended radio sources.

However Bergamini *et al.* (1967), and also Rees (1967), have pointed out that the cosmological increase in the 2.7 K radiation energy density can greatly ease the requirements on magnetic fields. For example, at a redshift of 5, a field of several microgauss is required. This field is considerably lower than the values derived from equipartition arguments in many of the extended radio sources. A diffuse X-ray spectrum with slope one-half power steeper (due to the Compton losses) than the radio spectrum, or approximately 1.3, is produced, with the additional requirement that the extragalactic radio background is produced almost entirely by extended radio sources at $z \approx 5$.

The difficulties arise in this theory when one attempts to explain the spectral features of the isotropic X-ray background. A $\frac{1}{2}$-power photon break at E_b arises when the loss-time of the electrons by, say, adiabatic losses, becomes equal to the inverse Compton loss time. Now according to equation (1), $E_b = \frac{4}{3}\,\gamma_{cr}^2 E_{ph}$, where $E_{ph} \equiv 7 \times 10^{-4}$ $(1+z)$ eV is the energy of a 2.7 K black-body photon, and the Compton loss-time t_c is given by Equation (2). If t_A denotes the adiabatic loss-time, then we obtain

$$E_b|_{z=0} \approx \left(\frac{10^6\ \mathrm{yr}}{t_A}\right)^2 \frac{1}{(1+z)^8}\ \mathrm{GeV}. \tag{12}$$

Hence E_b varies as the second power of the adiabatic loss time, which is associated with the expansion of the radio source, and as the eighth power of the redshift at which the X-rays are produced. Felten and Rees (1969) have applied the radio source model of Rees and Setti (1968) (which specifies t_A in terms of z),* and argue that a choice of $z = 4.5$ (Setti and Rees, 1969) will give a break at 20 keV. On the other hand, a similar study of inverse Compton emission by scattering of electrons in radio galaxies (Fukui and Hayakawa, 1969) concludes that even with $z \sim 10$, fields as low as 2×10^{-7} G would be required in order to account for the diffuse X-rays. Fukui and Hayakawa also found that the flattening in the X-ray spectrum occurs below 1 keV. The differences between these results and the earlier work previously described arise because Fukui and Hayakawa based their study on typical observed radio galaxies, and chose $t_A = 10^7$ yr.

In view of the immense degree of variation one might expect in t_A for different radio sources, together with a spread in z that might reasonably be expected, it is very difficult to understand how, when one adds the contribution from all radio sources, this model can give anything but an extremely gradual break, over a factor of $10^2 - 10^3$ in photon energy (and then only by one-half power). In this type of model, the observed break acts merely as a constraint on radio source evolution.

One might also add that this theory does not attempt to account for the $\frac{1}{4}$ keV excess, nor for the possible excess at 1 MeV. Finally, it may be noted that the recent detection at X-ray energies of Centaurus A (Bowyer *et al.*, 1970; Byram *et al.*, 1970) sets a strict lower limit on the magnetic field allowed in the extended lobes of radio emission surrounding this galaxy. The field cannot be more than a factor of 2 or 3 below its equipartition value, otherwise the ultrarelativistic electron flux would produce excessive inverse Compton radiation by scattering off of the 2.7 K cosmic black body radiation.

* In this model, the ram-pressure of the IGM is used to slow down the expansion, and the time-scale t_A varies as $(n/W)^{1/2}$, where W is the relativistic particle content of the source, and $n = n_0\,(1+z)^3$ is the particle density.

C. INVERSE COMPTON RADIATION FROM SEYFERT GALAXIES

In a recent paper, Longair and Sunyaev (1969) have proposed that inverse Compton scattering of relativistic electrons with infrared photons in the nuclei of Seyfert galaxies is the source of the diffuse X-ray background above 1 keV. The break at 40 keV is produced by inverse Compton losses in the nucleus. The electrons are assumed to diffuse out into the IGM, without suffering serious adiabatic losses, and inverse Compton scatter off of the 2.7 K black-body radiation to produce a soft X-ray spectrum of slope similar to that for the hard photons above the break.

Although this suggestion is attractive in that it offers an energy source, namely the infrared emission from Seyfert galaxies, which need only be converted to hard photons with one percent efficiency, there are some difficulties. In particular, conditions in Seyfert nuclei must be remarkably homogeneous in order to maintain the break in the diffuse X-rays. The relativistic electrons must also escape from Seyfert nuclei presumably by violent events of some kind, to avoid appreciable adiabatic losses. Finally, one would expect to detect Seyferts as discrete X-ray sources: since Seyferts form 1–2% of ordinary galaxies, the X-ray luminosity of a typical Seyfert is required to be comparable to that of M87.

4. Isotropic Gamma Ray Background: Diffuse Origin

Both the inverse Compton and nonthermal bremsstrahlung mechanisms produce diffuse γ-radiation as well as X-radiation; some special features are briefly summarized in this and the following section, and other proposed mechanisms are discussed. We consider in this section those theories which utilize a diffuse origin.

A. INVERSE COMPTON RADIATION

In the Brecher-Morrison (1969) model, the diffuse X-ray spectrum flattens slightly above 1 MeV due to the dispersion in spectral index of the injected electrons. However the flattening is insufficient to account for the excess found by Vette *et al.* (1970) in their highest energy channels.

The relativistic electron spectra must steepen at high energies, due to losses within normal galaxies themselves, caused by synchrotron and inverse Compton radiation. If the leakage time is $\sim 10^6$ yr, this steepening produces a corresponding one-half power break in the inverse Compton γ-ray spectrum above about 100 MeV. Even with a longer leakage time, it seems difficult to make the Brecher-Morrison model compatible with the limit on 100 MeV isotropic γ-radiation (Clark *et al.*, 1968; Garmire, 1970), cf. Figure 4.

B. NONTHERMAL BREMSSTRAHLUNG RADIATION

The flattening of the bremsstrahlung spectrum by one power of energy near 1 MeV, together with the piling up of Compton-scattered electrons in the burst model, offers a promising way of accounting for the Vette *et al.* observation (Figure 10). There may be a bremsstrahlung contribution at higher energies from the continuous injection model: the slope would be equal to the electron spectral index.

C. COSMIC RAY *p-p* INTERACTIONS

Several authors have estimated the flux of isotropic γ-rays, resulting from π^0-production by *p-p* collisions of cosmic rays with the intergalactic gas (cf. Ginzburg and Syrovatskii, 1964; Gould and Burbidge, 1965; Garmire and Kraushaar, 1965). A characteristic broad spectrum is produced, which peaks at 70 MeV.

Cosmological effects have only been recently included, by Stecker (1969). Cosmological expansion is extremely important, as the cosmic ray flux must be much greater at early epochs because of the adiabatic expansion losses. Consequently the γ-ray fluxes can be greatly enhanced. The spectrum peaks at 70 MeV/$(1+z)$ for injection at redshift z (Figure 11). This model can account for the spectral form of the Vette *et al.*

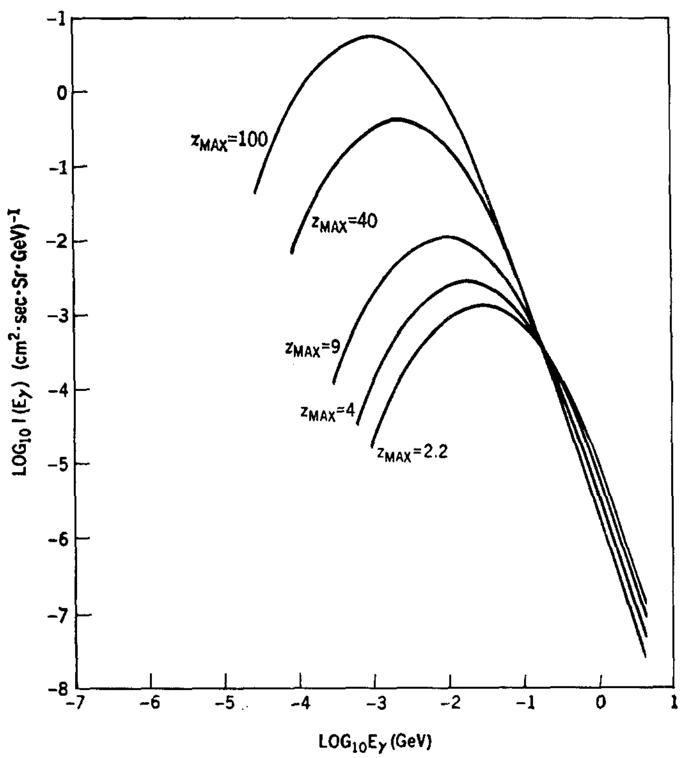

Fig. 11. Metagalactic γ-ray spectra from cosmic ray *p-p* interactions, based on a cosmic ray flux produced by burst injection at $z_{\max}$ (Stecker, 1969). The IGM is assumed to be transparent for $z < z_{\max}$.

excess above 1 MeV provided one chooses $z \sim 100$, and requires continuous injection of the cosmic rays (see D below), although the upper limit at 100 MeV (Clark *et al.*, 1969) requires the cosmic ray spectrum to be rather steeper than the index $\gamma = 2.6$ used by Stecker. In fact, the most comprehensive set of data on radio spectral indices, from the Parkes catalogue (Day *et al.*, 1966; Shimmins *et al.*, 1966), indicate a mean radio spectral index $\alpha=0.88$, with a variance about this value of 0.10. Consequently, the electron spectral index $\gamma=2\alpha+1$ may plausibly be chosen to be as large as 2.8, with presumably a similar value for the proton spectral index. The metagalactic cosmic ray flux required is only 10^{-4} of the galactic flux, if the mean density of the IGM is 10^{-5} cm^{-3}. Figure 12 illustrates the cosmic ray requirements as a function of the redshift at which injection first occurs. At very high energies ($E \gg 70$ MeV) the energy spectral index is 2. With injection at very high redshifts, absorption of γ-rays by the production of electron positron pairs may be important at energies greater than $10^6 (1+z)^{-2}$ GeV (Fazio and Stecker, 1970).

The main constraint on this theory is the fertile imagination required in order to construct sources of cosmic rays at $z \sim 100$. Since the object with greatest known redshift is currently the QSO 4C 05.34 at $z=2.877$ (Lynds and Wills, 1970), it is appar-

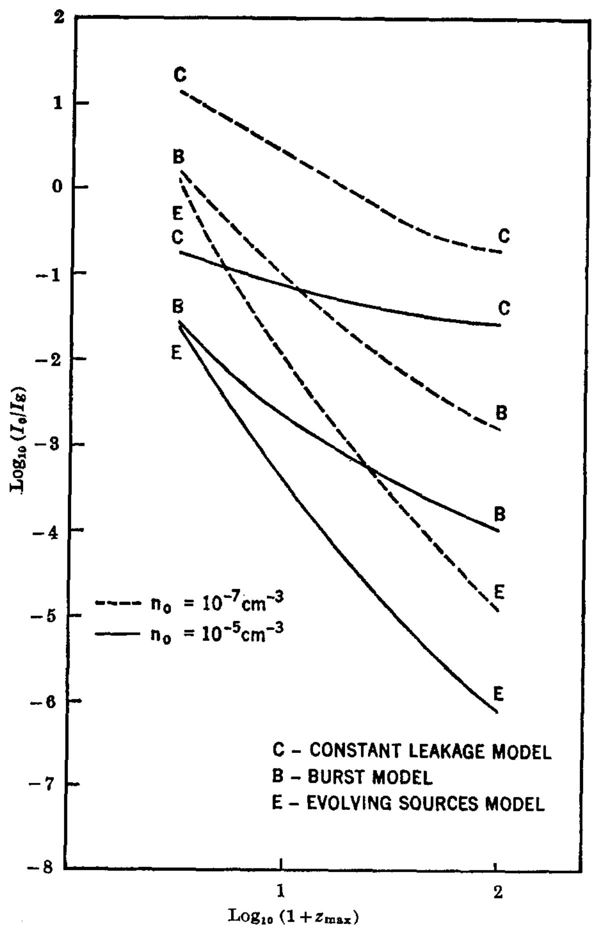

Fig. 12. Metagalactic proton intensity upper limits, for different modes of injection, plotted as a function of z_{max} (Stecker and Silk, 1969).

ent that one has only theoretical arguments about galaxy formation to shed light on the physical conditions at $z=100$. At best, it may be said that these arguments are inconclusive.

It is curious, however, to note that matter-anti-matter annihilation may provide a prolific source of γ-radiation at large z. Indeed, here the problem is to avoid excessive γ-radiation if one has an initially asymmetric Universe containing equal amounts of matter and anti-matter. Schatzman (1970) has pointed out that in such a situation, one might be able to restrict the amount of annihilation by the presence of a magnetic field. The observed γ-rays are mostly produced at a redshift of between 60 and 200, where the Universe first becomes transparent to the annihilation photons. Since the annihilation radiation spectrum peaks at 70 MeV, this model may lead to a more significant cosmological interpretation of the Vette *et al.* excess.

Injection at small $z(\sim 2$–$3)$ would require the metagalactic cosmic ray flux to be roughly ten percent of the galactic flux (with $n_0=10^{-5}$ cm^{-3}) in order to account for the 100 MeV observation of isotropic γ-rays.

D. INTERACTION OF COSMIC γ-RAYS WITH INTERGALACTIC MATTER

Arons and McCray (1969) and Rees (1969) have pointed out that X-rays and γ-rays produced at large redshift interact with intergalactic matter by Compton scattering. For example, with $n_0=10^{-5}$ cm^{-3}, then in a model which required the diffuse X-rays to originate at $z\gtrsim 10$, a bite would be taken out of the diffuse X-ray background between $\sim(1+z)^{-2.5}$ MeV and $\sim 0.02\,(1+z)^{1/2}$ MeV. At higher photon energies the reduced Klein-Nishina cross-section ensures that the transparency of the universe increases; at lower energies Compton scattering is never a significant energy drain (Figure 13).

Arons (1971) has studied the radiative transfer of isotropic X- and γ-radiation in an expanding medium, and has shown that burst injection of the diffuse X-rays into the IGM implies that the burst redshift $\lesssim 10$, if $n_0\gtrsim 10^{-7}$ cm^{-3}. Only with a conti-

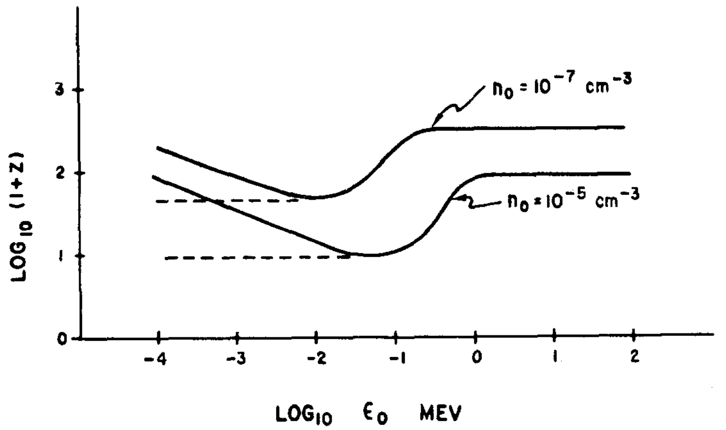

Fig. 13. Maximum visible redshift plotted against observed photon energy ε_0 (Arons and McCray, 1969). Solid curves: diffuse background flux. Dashed curves: discrete sources. Opacity includes both pair production and Compton scattering.

nuous injection of X-rays can one obtain an appreciable spectral effect: even this requires $z \sim 30$ ($n_0 = 10^{-5}$ cm^{-3}), or $z \sim 100$ ($n_0 = 10^{-7}$ cm^{-3}). Consequently, although one could perhaps fit this effect to the observed steepening in the X-ray spectrum above 40 keV and flattening above 1 MeV, one requires models with injection at very large z.

5. Isotropic γ-Ray Background: Discrete Source Mechanisms

A. INVERSE COMPTON SCATTERING IN RADIO GALAXIES

Maraschi *et al.* (1968) have extended the Bergamini *et al.* (1967) model of the diffuse X-ray background to γ-ray energies. The Vette *et al.* excess of 1 MeV cannot easily be explained in this model; also one would obtain too great a flux at 100 MeV unless some steepening occurs of the electron spectrum (assuming that the same electron spectrum accounts for the diffuse X-ray flux). Since the electron spectrum is already steepened by inverse Compton losses, this steepening must be intrinsic to the source spectrum of electrons, occurring at $\sim 10^3$ GeV. This could perhaps be related to the physical conditions in the nuclei of the radio galaxies, where the electrons are presumably accelerated, although the details of this theory remain to be investigated.

B. NORMAL GALAXIES

The contribution from our galaxy to the diffuse flux near 1 MeV is not known, as the measurements in this region have thus far utilized omnidirectional detectors. The 1 MeV excess could therefore be entirely of galactic origin (see Paper II).

Clayton and Silk (1969) have estimated the contribution to the isotropic diffuse γ-ray flux produced by radioactive decays of the processed matter ejected by supernovae in external galaxies. These γ-ray lines are emitted when ^{56}Ni decays to ^{56}Fe, and range in energy from 0.2 to 3.5 MeV. Since the decays occur within 77 days of the supernova explosion, supernovae in our own galaxy would not be detectable (since supernovae occur at a rate of 0.03 yr^{-1} at most). However supernovae in external galaxies would make a significant contribution to the diffuse flux near 1 MeV (Figure 14). The only assumption in this calculation is that all the ^{56}Fe in the galaxy is produced in this manner: one then knows the number of γ's per ^{56}Fe nucleus. If the ^{56}Fe is produced at a uniform rate, one has a peak at the rest energy of the line, with a smaller contribution from distant galaxies. However, if the ^{56}Fe is mostly produced when the galaxies were very young, the peak is redshifted correspondingly. Note that in neither case do the lines get completely smeared out by the differential expansion of the universe – a ledge should be detectable.

The motivation for this calculation was the excess flux above 1 MeV: unfortunately, the highest channel of Vette *et al.* (1970) from 4.5 to 6 MeV appears to contain a significant number of counts that cannot be explained by these γ-lines.

The isotropic flux reported by Clark *et al.* at 100 MeV cannot be due to normal galaxies, because the intensity of galactic γ-rays is only a factor of 3 higher at this energy. Normal galaxies therefore fail to account for the possible isotropic flux at 100 MeV by about one order of magnitude.

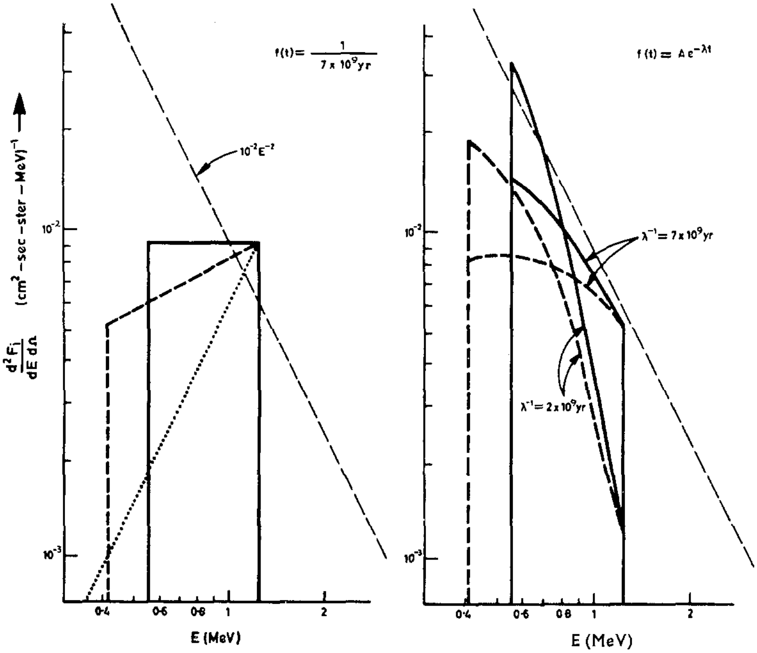

Fig. 14. Diffuse flux from supernovae in external galaxies due to a typical γ-ray line, that of ^{56}Co at 1.24 MeV (Clayton and Silk, 1969). Models of constant production of ^{56}Fe over a period of 7×10^9 yr are shown on the left, and models of exponentially decreasing production over a period of 7×10^9 yr are shown on the right. Contrasting cosmological models corresponding to a low-density universe (solid line) and an Einstein-de Sitter universe (dashed line) are shown in each case. The steady-state universe (dots) is shown on the left. The approximation $10\,E^{-2}$ cm^{-2} sec^{-1} $ster^{-1}$ MeV^{-1} for the flux in the diffuse background is shown for comparison.

6. Summary

A. SPECTRAL FEATURES

The ability of the various theories to explain the three main spectral features at $\frac{1}{4}$ keV, 60 keV and 1 MeV is summarized in Tables II and III.

Clearly, confirmation of the reality of these features, especially the soft X-ray and γ-ray excesses, is one of the key elements in enabling us to decide between the competing theoretical interpretations.

B. ENERGY REQUIREMENTS

None of the proposed interpretations are easily explained in terms of the available energy in cosmic rays (except perhaps the Seyfert galaxy proposal, and this runs into difficulties). It seems that one either has to regard normal galaxies at the present epoch as prolific sources of cosmic rays ($\sim 10^{60}$ erg/galaxy in protons), as is required by the Brecher-Morrison model, or to argue that at early stages in their evolution far more energy is available than at present. One ends up with much the same energy requirement in this approach.

TABLE II
Origin of isotropic diffuse X-radiation

Energy range	Mechanism	No evolution		Evolution		Predicted spectral features
		Diffuse	Discrete source	Diffuse	Discrete source	
< 1 keV	Thermal bremsstrahlung	X				Excess ar 0.25 keV
	Nonthermal proton bremsstrahlung			X		Excess at 0.25 keV
	Inverse Compton	X				Excess at 0.25 keV
					X	No excess
	Normal galaxies				X	Excess at 0.25 keV Continuum or lines
1 keV–1 MeV	Inverse Compton	X				Break predicted
			X			Break predicted
					X	Break predicted
	Nonthermal proton bremsstrahlung			X		Break predicted
	Normal galaxies				X	Break possible
	Nonthermal electron bremsstrahlung			X		Break predicted

One could conceivably identify such an early phase with the radio galaxy or QSO phenomena: in any event, cosmological evolution plays a major role. Cosmology does ease the energy requirements, but only for the inefficient mechanisms, such as nonthermal bremsstrahlung or π^0-production.

It seems that one still needs the metagalactic cosmic ray flux to be $\sim 10^{-2}$ of the galactic flux in the diffuse inverse Compton models, and 10^{-2}–10^{-4} in the nonthermal bremsstrahlung models.

Faced with problems of energetics, one is tempted to turn to the most energetic objects in the Universe, namely Seyfert nuclei and QSO's, to provide the basic energy source, whether directly or indirectly, for the diffuse X-ray background. A direct connection could be more readily investigated when X-ray observations are available of more extra-galactic sources.

C. ANGULAR VARIATIONS

Another approach, complementary to that of looking for remote discrete sources, is to seek angular fluctuations, or limits on such fluctuations in the diffuse X-ray background.

The best results presently available are those from the X-ray experiment on board OSO 3. Schwartz (1970) reports a limit of $\delta I/I \sim$ four percent on small-scale ($\sim 10°$) fluctuations over 10–100 keV over about one-quarter of the sky. If one assumes a

TABLE III

Origin of isotropic diffuse γ-radiation

Energy range	Mechanism	No evolution		Evolution		Predicted spectral features (relative to extrapolated X-ray spectrum)
		Diffuse	Discrete source	Diffuse	Discrete source	
1 MeV–10 MeV	Inverse Compton				X	No excess
		X				Small excess
	Supernovae in normal galaxies		X			Small excess
	p-p collisions at $z \sim 100$			X		Excess
	Matter-anti-matter annihilation at $z \sim 100$					
	Nonthermal bremsstrahlung			X		Excess
	Arbitrary			X		Small excess at large z
$>$ 10 MeV	Inverse compton				X	
		X				$\sim E^{-1.3}$ ($E <$ 100 MeV) $\sim E^{-1.8}$ ($E >$ 100 MeV)
	p-p Collisions			X		$\sim E^{+4}_{-2}$ for $E \lessgtr 70/(1+z)$ MeV
	Nonthermal bremsstrahlung			X		$\sim E^{-m-2}$ (proton) $\sim E^{-m}$ (electron)

uniform distribution of point sources of constant apparent brightness, one obtains

$$\delta I/I \approx (N\Omega)^{-1/2} \tag{13}$$

where N is the number of sources per steradian and Ω is the solid angle subtended by the detector. This yields $4\pi N > 10^5$ sources, for $\Omega = 0.12$ ster.

This case corresponds to having most of the sources at a remote distance. If in fact the sources are uniformly distributed, and are of constant *absolute* luminosity, one obtains

$$\delta I/I \approx (\Omega N)^{-1/3} \tag{14}$$

In this case, Schwartz's result yields $4\pi N > 4 \times 10^6$. This is about an order of magnitude less than the observed number of clusters of galaxies (Allen, 1963). Better limits on $\delta I/I$ and use of smaller solid angle detectors should enable this limit to be considerably improved.

At some point, small-scale fluctuations must be found in the diffuse X-ray background. This is because even in the diffuse models, sources are ultimately responsible for producing the particles which radiate. An interesting prediction can be made, concerning the dependence of fluctuations on photon energy. This should be an extremely model-dependent phenomenon.

For example, in the diffuse inverse Compton model, the distance travelled by the ultrarelativistic electrons decreases as a function of energy. The angle subtended by a fluctuation of scale R is given as a function of redshift by $\alpha \approx R H_0 f(z)/c$, where (e.g., see McVittie, 1965)

$$f(z) = \frac{q_0^2 (1+z)^2}{q_0 z + (q_0 - 1)\{(1 + 2q_0 z)^{1/2} - 1\}}$$

At higher photon energies, larger angular fluctuations α are expected, and would be given by

$$\alpha_{IC} \approx 3.3\, \varepsilon_{\mathrm{keV}}^{-1/2} z^{-1} (1+z)^{-2} \deg, \tag{15}$$

(where we have set $q_0 = 1$ or $q_0 = 0$) if one makes the simplifying assumption that cosmic ray electrons propagate rectilinearly. α_{IC} corresponds to the angular distance an ultrarelativistic electron would travel before losing most of its energy.

The thermal bremsstrahlung interpretation of the diffuse soft X-rays would also imply angular variations, if the gas distribution is similar to that of the galaxies. For example, the study by Limber (1954), quoted in the earlier discussion of thermal emission, implies a characteristic scale for fluctuations in the distribution of galaxies $\langle r \rangle \sim 5$ Mpc. (We have corrected Limber's value for $\langle r \rangle$ to take account of the revised distance scale.) If the diffuse matter required to be at $\sim 10^6$ K (to account for the observed $\frac{1}{4}$ keV flux) follows a similar distribution to that of galaxies, fluctuations of $\sim 0.1°$ would be expected. A detector of solid angle Ω would measure fluctuations

$$\delta I/I \approx \Omega^{-1/3} (\langle r \rangle / R), \tag{16}$$

where $R \approx c/H_0 \approx 4000$ Mpc.

In fact, diffuse matter in groups and clusters of galaxies may well be the predominant form of intergalactic matter. Since the diffuse matter in clusters would attain a temperature corresponding to the mean velocity dispersion among the galaxies, the fluctuation scale length for the thermal emission is given by the mean diameter of the contributing systems of galaxies. Groups of galaxies have a mean velocity dispersion of 200–300 km/sec, and the mean diameter of 50 nearby groups catalogued by de Vaucouleurs (1970) is $\langle r \rangle \sim 6$ Mpc.

On the other hand, clusters of galaxies have a somewhat higher dispersion in velocities, amounting to 500–1000 km/sec, and the average diameter of 15 clusters for which data is available is $\langle r \rangle \sim 3$ Mpc.

Diffuse matter in groups of galaxies could conceivably account for the diffuse X-ray background at low energies, and that in clusters at energies up to 10 keV. In either case, fluctuations would be predicted according to Equation (16). Limits on such fluctuations could be used to set limits on the possible amount of intra-cluster matter.

It is of interest to note that, if the 'missing mass' required to bind the Coma cluster were in gaseous form, the gas must be ionized and its temperature cannot exceed $T \sim 5 \times 10^5$ K (Rees *et al.*, 1968). The gas would absorb soft X-rays sufficiently to cause a shadow effect on the background of 0.25 keV if it were of Population II composition (assuming $T < 5 \times 10^5$ K). However strong theoretical arguments have recently been advanced that make the hypothesis of such a relatively cool intracluster medium seem implausible (Turnrose and Rood, 1970).

Nonthermal bremsstrahlung theories of the origin of the diffuse X-rays above 1 keV lead to a prediction for the energy-dependence of fluctuations that contrasts markedly with the fluctuations expected on the basis of an inverse Compton origin. Since cosmic rays are stopped more efficiently at lower energies, one would therefore expect fluctuations to *decrease* in scale with *increasing* photon energy.

The range of a fast electron of energy E MeV is

$$R \approx 10^4 (10^{-5}/n)\, E^2 \text{ Mpc}^*$$

The corresponding angular fluctuation in the X-ray background, assuming rectilinear propagation, is

$$\alpha_{NTB} \approx RH_0 f(z)/c \approx 1.4 \left(\frac{\varepsilon}{100 \text{ keV}}\right)^2 \frac{1}{z(1+z)} \left(\frac{10^{-5}}{n}\right) \text{deg} \tag{17}$$

for a $q_0 = 0$ or $q_0 = 1$ cosmological model, and the nonthermal electron bremsstrahlung mechanism. In the case of suprathermal proton bremsstrahlung, equation (17) should be multiplied by a factor $(M/m)^{3/2}$.

In fact, free streaming of cosmic rays is likely to be a poor assumption. Suppose that the cosmic rays diffuse, with an effective mean free path λ. Expressions (15) and (17) should now be multiplied by a factor $(\lambda/3Vt_0)^{1/2}$. With $\lambda \sim 1$ Mpc, this factor amounts to $\sim 10^{-2}$.

* This expression should be multiplied by a factor $(m/M)^{1/2}$ to obtain the range of a fast proton.

Clearly these results are over-simplified, but the qualitative differences may nevertheless enable these two mechanisms to be distinguished.

By contrast, discrete source models would seem to imply no dependence of fluctuation on photon energy. One finds that the number of sources needed to reproduce the diffuse background near 1 keV in either a $q_0=1$ or $q_0=0$ cosmology is (Felten and Rees, 1969)

$$N \approx 5 \times 10^3 (10^{46} \text{ erg sec}^{-1}/P)\, z^2 (1+z)^{-0.3} \text{ ster}^{-1},$$

where P is the luminosity of a typical source in X-rays over 1–10 keV. An X-ray luminosity of $\sim 10^{46}$ erg/sec is reported for the quasi-stellar radio source 3C 273 by Bowyer *et al.* (1970) and Friedman (1970).

The predicted fluctuation, assuming standard sources at this luminosity, is

$$\delta I/I \approx 10^{-2} z^{-1} \Omega^{-1/2}.$$

For $\Omega=0.1$ ster, and $z=2$, fluctuations of order one percent are predicted.

Isotropy measurements may also be made over large angular scales. Schwartz (1970) reports an upper limit of two percent on a possible 24-h anisotropy from 10–30 keV over approximately one-half of the celestial sphere. Wolfe (1970) has emphasized that, because of the negative power-law character of the diffuse X-ray spectrum, the Compton-Getting effect (Compton and Getting, 1935; Gleeson and Axford, 1968), makes the X-ray background a sensitive monitor of global anisotropy. For example, the limit on any 24-h variation restricts the velocity of the earth to less than 800 km/sec in any direction, relative to a rest-frame in which the X-rays would appear isotropic. Although the microwave background anisotropy observations give a stronger limit, by about a factor of 3, only a relatively small region of the sky is covered (Partridge and Wilkinson, 1967; Conklin and Bracewell, 1967; Conklin, 1969).

Moreover the existence of a similar limit on possible 12-h anisotropy can set limits on large-scale shear and vorticity in the Universe that are of the same order as those set by the isotropy observations of the microwave radiation, if one makes the single assumption that a substantial fraction of the X-ray background originates at large redshifts ($z \gtrsim 10$) (Wolfe, 1970).

7. Conclusion

The discovery of the origin of the isotropic X-ray background is bound to shed light on processes of fundamental cosmological importance, relevant to the evolution of galaxies, and possibly of the Universe itself. Improved spectral and angular resolution will accelerate progress to this goal. At present, one is hard pressed to choose between the various competing theories summarized in Table II and III. Eventually, many of these theoretical speculations will become redundant, especially when improved observational and theoretical evidence becomes available of the physical conditions in galactic X-ray sources, supernovae, active galactic nuclei, radio galaxies and quasi-stellar objects. It seems highly probable that a major unsolved problem of high energy astrophysics, namely the origin of cosmic rays, is intimately linked to the origin of the X-ray background.

It may well be that no single mechanism suffices to account for the entire spectrum of isotropic X- and γ-radiation. Nature is sufficiently perverse for there to be a reasonable probability that several different processes are contributing, and considerable ingenuity will be required to ascertain which mechanism, if any, is assigned the dominant role in a given spectral region.

Acknowledgements

I am indebted to many colleagues for their help in the course of preparing this review. I have found especially useful a recent summary by Setti and Rees (1969), which discusses the theories of the origin of the isotropic X-ray background from a somewhat different viewpoint to that taken here. I would particularly like to thank J. Arons, K. Brecher, and R. McCray for many discussions of some of the theoretical aspects of this review, and the many experimenters who have continued to bombard me with preprints, and who have often allowed me to quote preliminary results that have been painstakingly acquired. I hope that their data has not been too grossly abused by the rapidly multiplying ranks of theoretical X-ray astronomers.

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