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STUDIES IN RADIO SOURCE STRUCTURE—III
Inverse Compton Radiation from Radio Sources

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Summary

Various consequences of the inverse Compton effect in radio sources are considered. Scattering of synchrotron radiation by relativistic electrons gives rise to a higher frequency flux, which can then be scattered a second time, and so on. The resulting 'Compton-synchrotron' spectrum is calculated for simple source models. The variable cores of quasars may emit more energy by the Compton effect than in the form of synchrotron radiation. The γ-rays resulting from repeated scatterings could collide with photons within the quasar, producing relativistic electron–positron pairs which would modify the spectrum of the radiation. Compton scattering of synchrotron radiation would also be important in sources whose magnetic field is weak, and in very inhomogeneous extended sources. Compton scattering of the primeval black body background limits the lifetime of relativistic electrons in sources and gives rise to an X-ray flux. This process is more important in sources with large red-shifts. Finally the contribution of inverse Compton emission to the observed X-ray background is considered briefly.

1. *Introduction*. The astrophysical importance of the inverse Compton effect was first recognized by Feenberg & Primakoff (1948), who pointed out that, despite the low radiation density in intergalactic space, ultra-relativistic electrons might lose significant amounts of energy by this process. The radiation resulting from inverse Compton scattering of the background radiation has been discussed by several authors (Felten & Morrison 1963, 1966; Hoyle 1965; Gould 1965; Felten 1965; Fazio, Stecker & Wright 1966), who have considered whether this process could account for the observed X-ray background. In compact and intense radio sources, such as quasars, inverse Compton scattering of synchrotron radiation may be important (Ginzburg & Syrovatsky 1965; Rees & Sciama 1965, 1966; Shklovsky 1965; Hoyle, Burbidge & Sargent 1966).

In this paper we consider the total radiation spectrum from a radio source, taking into account Compton scattering, and we discuss some further consequences of the inverse Compton effect in radio sources. The relativistic electrons in radio sources will scatter not only their own synchrotron radiation, but also any other radiation which is present, and we consider in particular scattering of the primeval black body radiation. For simplicity, we treat separately the scattering of synchrotron radiation (Section 3) and of the primeval radiation field (Section 4). This is justifiable since one of these will generally dominate the other by a large factor in actual sources.

2. *Inverse Compton scattering*. We summarize in this section the basic facts about the inverse Compton effect, making the approximations which are justified in astrophysical applications.

Suppose that an electron of energy $E(\gg m_0c^2$, where m_0 is the rest mass of an electron) moves through an isotropic radiation field of energy density

$$\mathscr{E}_{\text{rad}} = \int \mathscr{E}_{\text{rad}}(\nu)d\nu \tag{1}$$

in a radio source. The radiation which is scattered by a relativistic electron will appear, in the source's frame, to be concentrated in a narrow cone in the direction of the electron's motion. The scattering of radiation of frequency ν can be treated classically if

$$h\nu E \ll (m_0c^2)^2 \tag{2}$$

Provided that equation (2) holds for all frequencies of radiation present in the source, the rate at which an electron loses energy is

$$-\dot{E}_c = c\sigma_T\mathscr{E}_{\text{rad}}\left(\frac{E}{m_0c^2}\right)^2 \tag{3}$$

where σ_T is the Thomson cross-section. The radiation which is produced when electrons of energy E scatter radiation of frequency ν has a spectrum which peaks at

$$\sim \tfrac{4}{3}\nu\left(\frac{E}{m_0c^2}\right)^2 \tag{4}$$

and has a logarithmic slope $\sim +1$ at lower frequencies. The energy losses suffered by electrons do not depend on ν explicitly provided that equation (2) holds, and are the same as the synchrotron losses which they would experience if they moved in a randomly oriented magnetic field of the same energy density as the radiation.

In the opposite extreme case, when

$$h\nu E \gg (m_0c^2)^2 \tag{5}$$

the high energy limit of the Klein–Nishina cross-section is applicable, and the frequency ν of the radiation enters explicitly into the formula for the energy loss. The total loss rate is then given by an integral

$$-\dot{E}_c = \tfrac{3}{8}c\sigma_T\int \mathscr{E}_{\text{rad}}(\nu)\left(\frac{m_0c^2}{h\nu}\right)^2 \log\left(\frac{2Eh\nu}{m_0{}^2c^4}+\tfrac{1}{2}\right)d\nu \tag{6}$$

and the scattered photons nearly all have energy $\sim E$. For a given value of $\mathscr{E}_{\text{rad}}$ the rate of loss of energy is very much less when equation (6) applies than it would be if the frequency of the radiation were so low that equation (4) were satisfied.

There is a possibility that electron–positron pairs may be produced by collisions between electrons and photons when equation (5) holds, but this process is in general less likely than Compton scattering, and will be neglected here. We shall likewise ignore double Compton scattering, in which a second photon is formed in the scattering process. If the relativistic particles move through a plasma of density n electrons per cm^3, the above formulae remain valid provided that the radiation being scattered has frequencies $\nu \gtrsim 10^4n^{1/2}E$ c/s; otherwise $(E/m_0c^2)^2$ must be replaced in equations (3) and (4) by $EE^*/(m_0c^2)^2$, where $E^*/m_0c^2 = 10^{-4}n^{-1/2}\nu$. This condition is certainly satisfied for the scattering of synchrotron radiation in extended sources. The value of n which is appropriate to the compact cores of quasars is very uncertain, but we are probably justified in neglecting the influence of ionized gas in this case also, and shall do so in the subsequent sections.

3. *Compton-synchrotron radiation from radio sources.* The synchrotron (S) radiation within a radio source can be Compton scattered by relativistic electrons, giving rise to radiation at higher frequencies. This (SC) radiation is liable to be scattered further, giving rise to what we shall call SC^2 radiation, and so on. In this section we calculate the spectrum of the radiation which results from these repeated scatterings.

The results will only be of interest in radio sources where the electrons radiate a significant fraction of their energy by the inverse Compton process. This requires in general that the energy density of the radiation within the source should be at least comparable with the energy density of the magnetic field. Clearly this *cannot* be the case in sources where both

(i) there is equipartition between the magnetic and relativistic particle energy densities, and

(ii) the electrons are able to traverse the whole source in their lifetime.

The magnetic field may, however, be below the equipartition value. Furthermore, at least in compact sources (such as the variable cores of quasi-stellar sources) the electrons are likely to be accelerated throughout the source and to have short lifetimes. In such cases the Compton losses may be comparable with, or even much greater than, the synchrotron losses.

We first consider, as an illustration, a uniform radio source in which the electrons have a differential energy spectrum $N(E) \propto E^{-\gamma}$ for $E_1 < E < E_2$. ($E_2 \gg E_1 \gg m_0c^2$). We assume that the source is transparent to all radiation, except to low frequency radio radiation for which synchrotron self-absorption may be important. (We discuss the validity of this assumption for actual sources later.) We also make the approximation that the synchrotron radiation within the source is isotropic and has uniform energy density. If $\gamma > \frac{1}{3}$ it is an adequate approximation to assume that the contribution of each electron to the synchrotron radiation is concentrated at a frequency $\nu_c(E) \sim 1{\cdot}2H(E/m_0c^2)^2$ Mc/s, where H is measured in gauss. The synchrotron spectrum of the source will have a high frequency cut-off at $\sim \nu_c(E_2)$. We assume further that the frequency ν_m at which the optical depth due to synchrotron self-absorption ~ 1, lies between $\nu_c(E_1)$ and $\nu_c(E_2)$. Between ν_m and $\nu_c(E_2)$ the logarithmic spectrum has slope $-(\gamma-1)/2$, and between $\nu_c(E_1)$ and ν_m the slope is 2·5. At even lower frequencies it would be ~ 2 (Rees 1967b), but this part of the spectrum comprises a negligibly small fraction of the energy radiated and can be ignored. Fig. 1 shows the spectra for three cases:

(a) $H \sim 10^{-5}$ G, $\left(\frac{E_1}{m_0c^2}\right) \sim 3 \cdot 10^2$, $\left(\frac{E_2}{m_0c^2}\right) \sim 3 \cdot 10^4$, $\nu_m \sim 10$ Mc/s

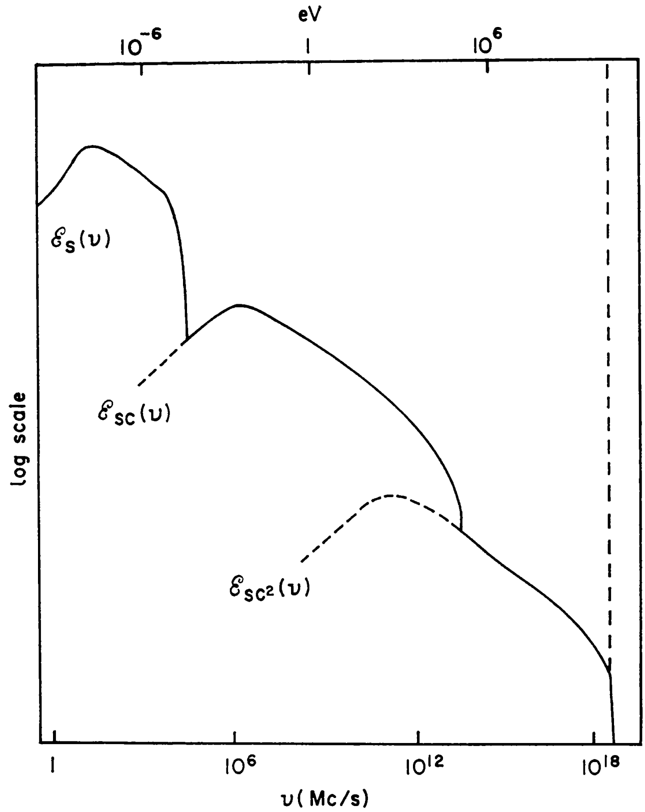
(b) $H \sim 1$ G, $\left(\frac{E_1}{m_0c^2}\right) \sim 10$, $\left(\frac{E_2}{m_0c^2}\right) \sim 500$, $\nu_m \sim 10^4$ Mc/s

(c) $H \sim 1$ G, $\left(\frac{E_1}{m_0c^2}\right) \sim 10$, $\left(\frac{E_2}{m_0c^2}\right) \sim 3 \cdot 10^4$, $\nu_m \sim 10^4$ Mc/s.

These might correspond respectively to a typical extragalactic radio source, and to the core of a quasi-stellar source in which (b) the synchrotron radiation is confined to radio frequencies, and (c) it extends to optical frequencies.

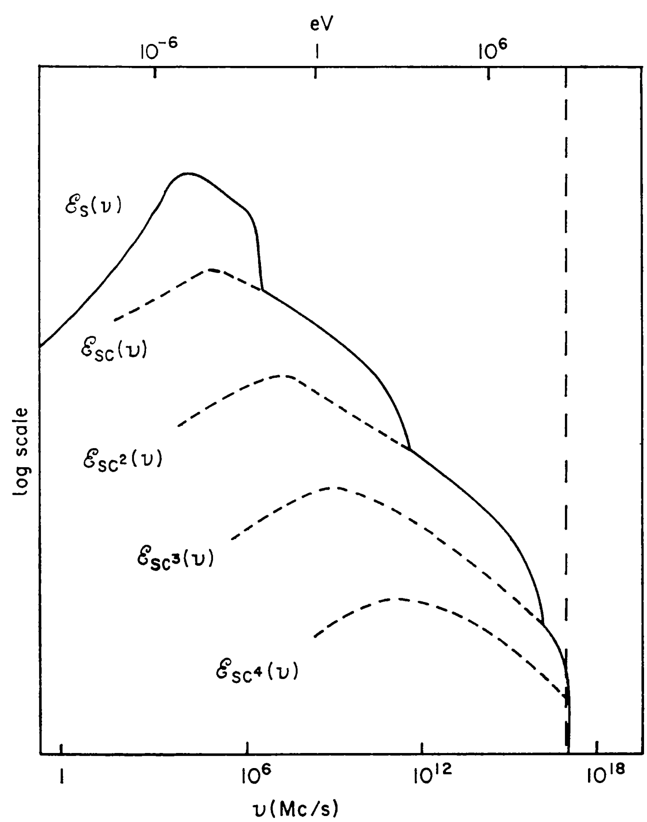
It is now a straightforward matter to calculate the energy density $\mathscr{E}_{SC}(\nu)$ of the SC radiation in the source at frequency ν. Using the approximation (4),

$$\mathscr{E}_{SC}(\nu) \propto \int_{E_1}^{E_2} \mathscr{E}_S\left(\tfrac{3}{4}\nu\frac{m_0^2c^4}{E^2}\right) N(E)dE \quad \left(\nu > \nu_m\left(\frac{E_1}{m_0c^2}\right)\right) \tag{7}$$



eV
10^{-6}
1
10^{6}
$\mathcal{E}_s(\nu)$
$\mathcal{E}_{sc}(\nu)$
$\mathcal{E}_{sc^2}(\nu)$
log scale
1
10^{6}
10^{12}
10^{18}
ν (Mc/s)

(a)



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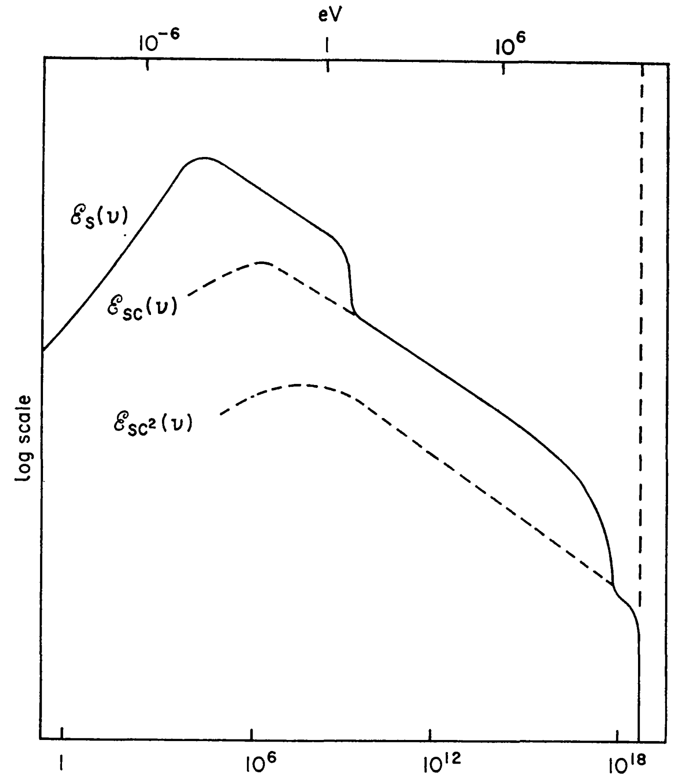
(b)



(c)

FIG. 1. *The Compton-synchrotron spectra from three uniform radio source models containing relativistic electrons with a power law spectrum. Further details are given in the text.*

provided that the classical formulae (2) and (3) can be applied. This will be so in all three cases illustrated in Fig. 1, and in fact in most sources in which the synchrotron spectrum does not extend beyond optical frequencies. $\mathscr{E}_{SC}(\nu)$ is spread over a wider range of frequencies than the synchrotron radiation and the spectrum has the same slope $-(\gamma-1)/2$ between $\sim(E_1/m_0c^2)^2\nu_m$ and $\sim(E_2/m_0c^2)\nu_c(E_2)$, apart from a logarithmic factor which causes the spectrum to curve downwards at the high frequency end. A low frequency component with slope ~ 1 arises mainly from scatterings by electrons of energy $\sim E_1$ in which the frequency of the radiation is raised by a factor $\ll (E_1/m_0c^2)^2$.

We can similarly calculate $\mathscr{E}_{SC^2}(\nu)$, $\mathscr{E}_{SC^3}(\nu)$ and so on. The classical formulae for the cross-section will not apply to all the 'higher order' scatterings; in fact we can only calculate $\mathscr{E}_{SC^n}(\nu)$ equations from (3) and (4) if

$$h\nu_c(E_2)\left(\frac{E_2}{m_0c^2}\right)^{2n+1} \ll m_0c^2. \qquad (8)$$

Otherwise it is necessary to use the Klein–Nishina formula to calculate the radiation which is produced when the highest energy electrons scatter the highest frequency radiation. If equation (8) does not hold, the spectrum extends up to a frequency ν such that $h\nu \sim E_2$ and then cuts off—obviously no photons can be produced whose energy exceeds that of the most energetic electrons present. These spectra are shown in Fig. 1. The slope of the synchrotron spectrum is preserved, apart from a curvature due to logarithmic factors which becomes more marked for the 'higher order ' spectra. In cases (a) and (c), equation (8) fails to hold even for $n = 2$, and in case (b) it breaks down for $n = 3$. It is unlikely to hold for values of n greater than about 4 in any radio source with realistic properties.

If synchrotron self-absorption did not occur at radio frequencies, we should simply have (for an isotropic distribution of electron velocities) $\mathscr{E}_{SC} = f\mathscr{E}_S$, where $f = \mathscr{E}_S/(H^2/8\pi)$. We should also have $\mathscr{E}_{SC^2} = f\mathscr{E}_{SC}$ if equation (2) were satisfied for $n = 2$. Provided that the spectral index α of the synchrotron radiation < 1 (i.e. $\gamma < 3$), the occurrence of synchrotron self-absorption does not greatly alter these results. The energy densities $\mathscr{E}_S$, $\mathscr{E}_{SC}$, $\mathscr{E}_{SC^2}$ and so on will be in geometric progression for as long as equation (8) can be applied, and then fall off rapidly. For example, in the situation shown in Fig. 1(b), suppose that the spectral index $\alpha \sim 0.5$ and that $f = 10$. Then

$$\mathscr{E}_S : \mathscr{E}_{SC} : \mathscr{E}_{SC^2} : \mathscr{E}_{SC^3} \sim 1 : 10 : 100 : \tfrac{1}{2},$$

and the values of $\mathscr{E}_{SC^n}$ for $n > 3$ would be completely negligible. This shows that consistent radio source models are possible in which the Compton losses greatly exceed the synchrotron losses (this point is made by Hillier (1966)).

Spectra resembling those of Fig. 1 would not maintain their shapes for longer than the lifetime of the shortest-lived electrons, unless the sources are rejuvenated by the continuous acceleration or injection of electrons with a suitable energy distribution. When the electrons radiate only by the synchrotron process they lose energy at a rate proportional to E^2, and the manner in which electron spectra evolve as a consequence of these losses is well known. If new particles are not injected, a cut-off (or under certain conditions merely a steepening of the spectrum) develops at high energies and subsequently progresses towards lower energies; if new electrons are injected at a constant rate with a differential energy spectrum $N_i(E) \propto E^{-\gamma}$, the electron spectrum in the source attains a steady state with $N(E) \propto E^{-(\gamma+1)}$ (for $\gamma \geqslant 1$), or $N(E) \propto E^{-2}$ (for $\gamma \leqslant 1$).

All these results must be modified when the inverse Compton effect is appreciable, since it is clear from equation (6) that the Compton losses are *not* proportional to E^2 unless all the radiation in the source has frequencies ν such that $h\nu < m_0^2c^4/E$. Provided that the spectrum of the radiation does not rise more steeply than $\propto \nu$ at high frequencies, the energy loss resulting from scattering the radiation for which $h\nu > m_0^2c^4/E$ can actually be neglected, so we have

$$\dot{E}_c \propto E^2 \int_0^{m_0^2c^4/hE} \mathscr{E}_{\text{rad}}(\nu)d\nu. \tag{9}$$

The integral in equation (9) is a function of E, and the energy loss rate increases with E more slowly than $\propto E^2$. If, for example, $\mathscr{E}_{\text{rad}}(\nu) \propto \nu^{-\alpha}(-1 < \alpha < 1)$, then $\dot{E}_c \propto E^{1+\alpha}$; thus for $\alpha < 0$ the higher energy electrons in fact have *longer* Compton lifetimes, and the electron spectrum in a source would not develop the above-mentioned break as a consequence of energy losses. Calculations of the evolution of source spectra are much less straightforward when we have to allow for the Compton effect, since the magnitude of the electron energy losses depends on the *spectrum* of the radiation as well as on its total energy density. The Compton effect is likely to be most significant in radio sources with small dimensions and high radiation density, in which the lifetimes of individual electrons are short and relativistic particles are being continually generated. We shall therefore discuss the problem of determining the steady state electron spectrum $N(E)$, and the associated Compton-synchrotron radiation spectrum $\mathscr{E}_{\mathrm{rad}}(\nu)$, in a source where electrons are injected at a steady rate with a given spectrum $N_i(E)$ per second per unit volume. $N(E)$ must satisfy the equation

$$\frac{d}{dE}(N(E)\dot{E}) = N_i(E), \tag{10}$$

where

$$-\dot{E} \propto E^2 \left\{ \frac{H^2}{8\pi}(1-x) \int_0^{m_0^2c^4/hE} \mathscr{E}_{\mathrm{rad}}(\nu)\,d\nu \right\}. \tag{11}$$

The factor x allows for reabsorption of synchrotron radiation, as discussed in Paper II (Rees 1967b), and $\mathscr{E}_{\mathrm{rad}}(\nu)$ is itself a function of $N(E)$ which is calculated

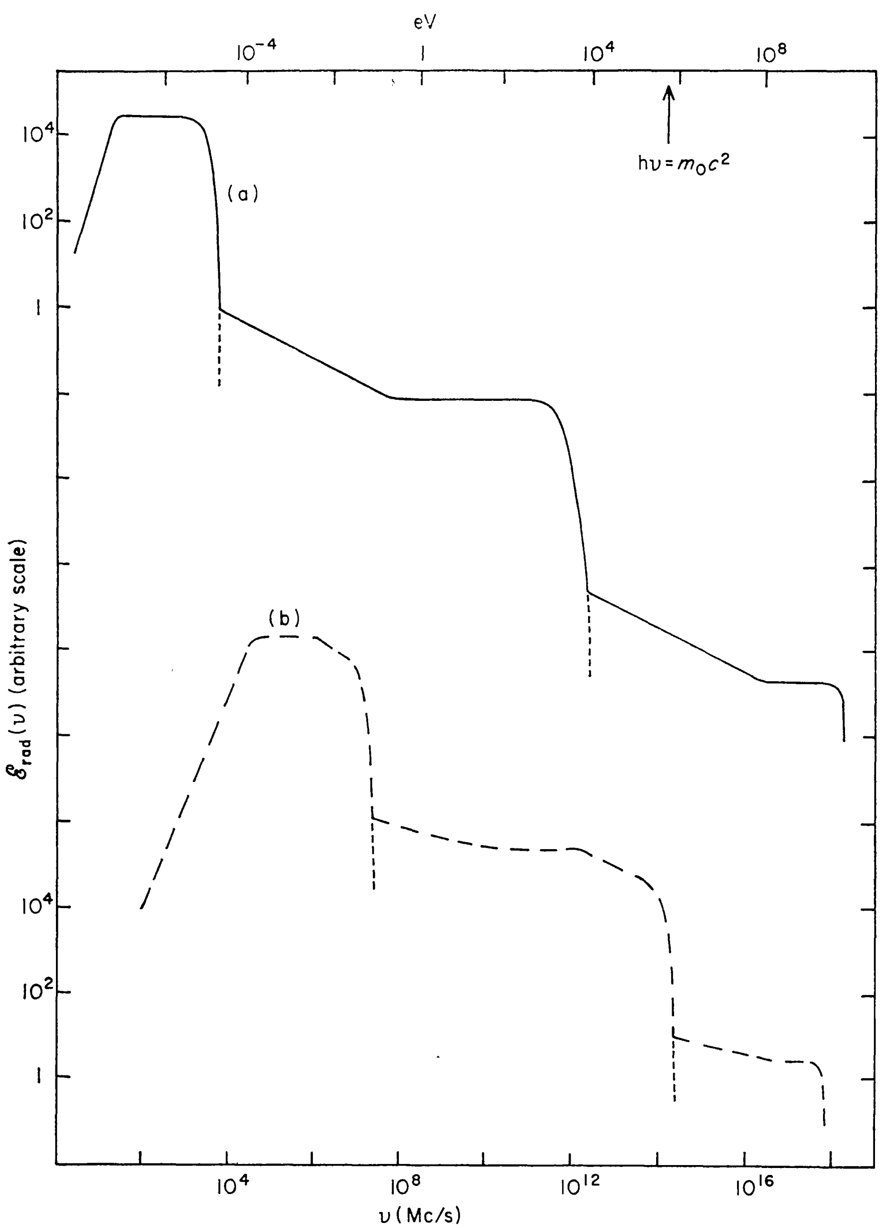


FIG. 2. *Two examples of steady state Compton-synchrotron spectra for sources in which monoenergetic electrons are being injected at a steady rate. The properties of the sources (a) and (b) are specified in the text.*

from equation (7). The shape of the steady state electron and radiation spectra depend not only on H and $N_i(E)$ but also on the dimensions ℓ of the source, since the total radiation energy density $\mathscr{E}$ must be given by

$$\mathscr{E} \sim \frac{\ell}{c} \int N_i(E) E dE \tag{12}$$

The Compton losses will certainly be important if $\mathscr{E} \gtrsim H^2/8\pi$. For given values of H and $\mathscr{E}$, and a given injection spectrum $N_i(E)$, there must be a self-consistent electron spectrum $N(E)$ which gives rise to a radiation spectrum $\mathscr{E}_{\rm rad}(\nu)$ such that the value of $\dot{E}$ calculated from equation (11) satisfies equation (10). Figs 2 and 3 illustrate the calculated steady state radiation and electron spectra respectively for two uniform sources characterized by the following (arbitrarily chosen) parameters, in which the injected electrons are mono-energetic:

(a) $H \sim 10^{-5}$ G, $\mathscr{E} \sim 10^{-7}$ ergs/cm^3, electrons injected with $E/m_0c^2 \sim 10^4$;

(b) $H \sim 1$ G, $\mathscr{E} \sim 10^3$ ergs/cm^3, electrons injected with $E/m_0c^2 \sim 3 \cdot 10^3$.

(Of course the same results will apply if the injected electrons have a power law spectrum flatter than $\propto E^{-1}$.) It turns out that in neither example is $N(E)$ simply proportional to E^{-2}, as would be the case if the Compton effect were negligible. The Compton-synchrotron radiation spectra, for both (a) and (b), are such that

$$\mathscr{E}_{\rm S} : \mathscr{E}_{\rm SC} : \mathscr{E}_{\rm SC^2} \sim 1 : 100 : 100.$$

The electrons with low E emit nearly 99 per cent of their energy at γ-ray frequencies by 'second-order' Compton scattering. For larger E, however, the main part of

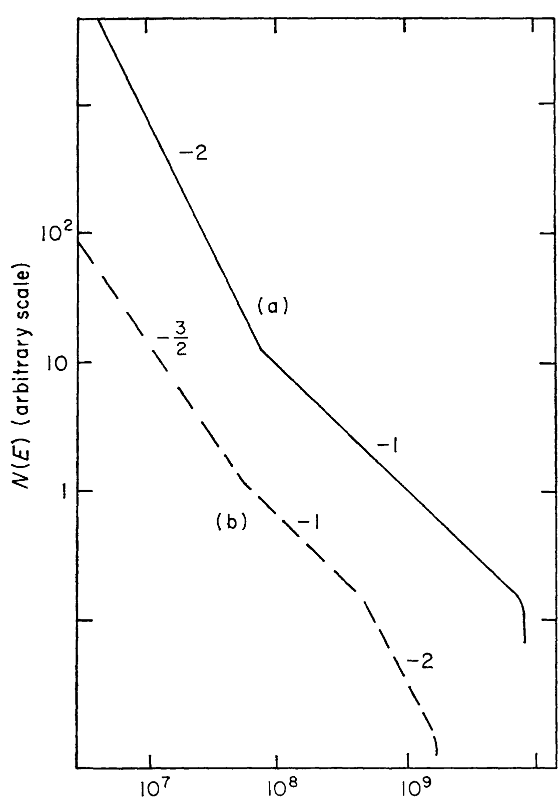


FIG. 3. *The steady state differential electron spectra N(E) corresponding to the two sources in Fig. 2. The logarithmic slopes are indicated.*

the SC radiation, which is at X-ray frequencies, has to be excluded from the integral in equation (11), and so the more energetic electrons contribute a smaller fraction of their energy to the SC^2 spectrum. The shapes of the graphs for $N(E)$ shown in Fig. 3, which reflect the dependence of $\dot{E}$ on E, are related to the radiation spectrum $\mathscr{E}_{\rm rad}(\nu)$ in the range $\sim 10^{10}$–10^{13} Mc/s ($\sim 10^2$–10^5 eV), and one can easily confirm that Figs 2 and 3 are indeed consistent. The synchrotron spectrum falls off at low frequencies as a consequence of self-absorption. According to Paper II (Rees 1967b) the low energy electrons should tend to gain rather than lose energy as a result of synchrotron emission and absorption, but in both our examples (a) and (b) this tendency is overwhelmed by the energy losses due to Compton scattering. If $\mathscr{E}$ were much lower, or H much higher, than in the specific examples we have discussed, the relaxation process discussed in Paper II could cause the low energy electrons, whose synchrotron emission is all reabsorbed within the source, to form an approximate Maxwellian or ‘ δ-function ’ distribution. Their main net loss of energy could then result from the Compton effect even if $\mathscr{E} \ll H^2/8\pi$.

We have assumed so far that sources are transparent to all radiation except to low frequency ($\nu \lesssim \nu_m$) synchrotron radiation, which is likely to be reabsorbed. At first sight this might appear inconsistent, since the entire inverse Compton radiation arises from photons which have encountered a relativistic electron before being able to escape from the source. However even when the Compton effect is important, as in the examples we have described, the fraction of the synchrotron photons which need to be scattered to produce the Compton radiation is usually negligible. For example, if $E_1/m_0c^2 \sim 1000$ and $\alpha \sim 0{\cdot}5$ in a source of the kind whose spectra are illustrated in Fig. 1, less than 1 in 10^5 of the synchrotron photons need to undergo Compton scattering in order that $\mathscr{E}_{\rm SC}$ should be as large as $\mathscr{E}_{\rm S}$. The probability that an individual photon is scattered, and the consequent depletion of the synchrotron radiation field, would only be appreciable if $\not{f} \gtrsim \overline{E^2}/m_0{}^2c^4$. In such extreme conditions a negligible proportion of the energy in the source would be emitted at radio and optical frequencies, since most of the *photons* (and *a fortiori* most of the energy) would emerge as X-rays or γ-rays.

A very compact and intense source may be opaque not only to low frequency radiation but also to γ-rays, and this can have interesting consequences. We have seen that sources such as those whose spectra are shown in Figs 1 and 2 may radiate much of their energy as γ-rays. Jelley (1966) has pointed out that, if γ-rays are produced in a source which also emits large amounts of radiation at optical and X-ray frequencies, they may be reabsorbed within the source as a result of collisions with photons, leading to the formation of electron–positron pairs. Since these electrons and positrons will be relativistic, they will themselves contribute to the synchrotron and inverse Compton emission. They will have a steeper spectrum than the relativistic electrons originally injected, and so they will in general cause the Compton-synchrotron spectrum below γ-ray frequencies to be steeper than we would calculate if we assumed that the γ-rays could all escape. This process would also turn a non-power law electron spectrum into a closer approximation to a power law.

A source need not have unreasonable properties to be opaque to γ-rays. If, for example $\sim 10^{46}$ ergs/s is emitted from a region of diameter $\lesssim 10^{18}$ cm in the form of 1–10 keV X-rays, the density of X-ray photons would be $\gtrsim 10^7$ cm^3, and the source would be opaque to γ-rays with energy greater than a few times 10^7 eV. The model (b) in Fig. 2 would be opaque if its dimensions were $\gtrsim 10^{15}$ cm.

If there is enough ionized gas present to make the source opaque to electron scattering, γ-rays would impart relativistic velocities to thermal electrons which scatter them, and these electrons would have a similar effect on the radiation spectrum of the source to the electron–positron pairs already described.

Relevance to observations

(i) *Cores of quasars*. Polarization has been detected in the light from 3C 446 (Kinman, Lamla & Wirtanen 1966), 3C 279 and 3C 345 (Kinman 1967), and possibly also 3C 273 (Schmidt 1965; Whiteoak 1966). This suggests that the optical continua of quasars are synchrotron radiation, or result from inverse Compton scattering of polarized radio frequency radiation. The observed optical variations in these sources indicate dimensions $\lesssim 10^{18}$ cm for the emitting region, and the energy density of radiation within this region would be $\gtrsim 1$ erg/cm^3. The inverse Compton effect would therefore be important if the magnetic field were weaker than ~ 1–10 G. In a much stronger field the Compton effect would be negligible unless the electrons could establish a roughly Maxwellian distribution in which their synchrotron losses were exactly compensated by self-absorption.

If the optical continuum is inverse Compton radiation, f must be $\gtrsim 1$. There should therefore be a strong flux of X-rays, and possible also γ-rays (as in Figs 1(b) and 2(b)). This would be true even if the source were very inhomogeneous. If, on the other hand, the optical continuum is, like the radio emission, synchrotron radiation (Fig. 1(c)), there need not be any associated Compton radiation at high frequencies. We clearly cannot decide between these two possibilities until observations are available of the intensity and spectrum of the X-ray emission from some quasars, but it would be possible to infer from such data the magnetic field strength, electron spectrum, and dimensions of the sources. The complicated shape of the radiation spectrum in Fig. 2(b), which corresponds to about the simplest conceivable type of source model, indicates that an observed spectrum with many changes in slope does not imply the presence of many components in the source.

One could make some deductions about the mechanism of the variations in quasars by comparing the observed flux variations in different frequency ranges. If the density of relativistic particles increases, but the magnetic field stays the same, the inverse Compton radiation becomes relatively more important. However if the rate of injection of electrons is constant but the magnetic field is increased, the synchrotron flux increases at the expense of the higher frequency (Compton) flux. The shapes of the synchroton spectra shown in Fig. 2 depend on $\mathscr{E}$ as well as on the spectrum of the injected electrons, so we would expect variations in the former even if the latter does not alter during the variations.

(ii) *Sources with weak magnetic fields*. There is evidence that the magnetic field strength in a few sources is less than the equipartition value. Such sources are especially likely to be strong emitters of X-rays and γ-rays by the inverse Compton effect. The quasi-stellar source 3C 286 has an angular diameter $\lesssim 0{\cdot}1''$ (this refers to the whole source and not to the central core considered in (i) which would be much smaller), and Williams (1966) calculates that the magnetic field cannot exceed 10^{-5} G. The energy density of the synchrotron radiation is then $\gtrsim 100(H^2/8\pi)$, and we would expect $\gtrsim 5 \,.\, 10^{46}$ ergs/s to be emitted at X-ray frequencies by the Compton effect (see Figs 1(a) and 2(a)). (There should also be a γ-ray flux, since the radiation density within the source would not be high enough for γ-rays to be reabsorbed.) Although this X-ray flux is not quite detectable with present techniques, the situation would change dramatically if a more stringent upper limit on the angular diameter θ could be derived from observations, since the expected X-ray flux $\propto \theta^{-10}$. The presence of inhomogeneities within the source would further increase the expected X-ray intensity. The observed absence of the predicted X-ray flux would imply either that the radio emission was not synchrotron radiation, or that the source has some special structure. For example the inverse Compton radiation would be very much reduced in a relativistically expanding source model of the type discussed in Paper I (Rees 1967a), or in the anisotropic model discussed by Woltjer (1966).

(iii) *Extended sources.* The strong radio galaxy Cygnus A emits $\sim 6 \cdot 10^{44}$ ergs/s at radio frequencies. It is a double source, the size of each component being $\sim 10^{23}$ cm. If the emission within each component were uniform, the energy density of synchrotron radiation would be $\sim 2 \cdot 10^{-12}$ ergs/cm^3, and f would be $5 \cdot 10^{-11}H^{-2}$. McCracken (1966) has suggested that Cygnus A is responsible for $\sim \frac{1}{2}$ of the X-ray flux observed from the Cygnus constellation. It would then need to radiate ~ 50 times as much energy in the X-ray range as at radio frequencies. If we attribute this flux to Compton scattering of the radio radiation, and assume that the components are uniform, we would require $H \sim 10^{-6}$ G, which is almost two orders of magnitude weaker than the equipartition field, but is still not impossibly low.

The estimates would alter if the source were inhomogeneous, and there is in fact evidence for the existence of fine structure within the components of Cygnus A (Wade 1966). Suppose that the emission were concentrated in ~ 10 regions each of dimensions ~ 300 pc. The radiation energy density within these subcomponents would be $\sim 2 \cdot 10^{-9}$ ergs/cm^3, and the required intensity of X-rays would be produced if the magnetic field were $\sim 3 \cdot 10^{-5}$ G. The X-rays could alternatively be interpreted as synchrotron radiation by very high energy electrons, though this theory runs into the difficulty that the relevant electrons would have very short lifetimes, and it would be difficult to understand how they could be continuously accelerated in a tenuous source.

4. *Inverse Compton scattering of the background radiation.* The relativistic electrons in radio sources will clearly scatter any other radiation which is present, as well as their own synchrotron radiation. The dominant form of radiation in extended sources may be the primeval black body radiation, which has a temperature $T \sim 3$ degrees and an energy density $\sim 10^{-12}$ ergs/cm^3 at the present epoch. In all homogeneous 'big bang' cosmologies the temperature and energy density of this radiation depend on the red shift z like $(1+z)$ and $(1+z)^4$ respectively.

Hoyle (1965) has pointed out that Compton scattering of the primeval radiation may be an important mechanism for the production of cosmic X-rays. When this radiation is scattered by an electron of energy $E(\gg m_0c^2)$, radiation is produced at frequencies $\sim 4 \cdot 10^{11}(1+z)(E/m_0c^2)^2$ c/s. If the synchrotron radiation from a source with red-shift z has a spectrum $\propto \nu^{-\alpha}(\alpha > \frac{1}{3})$ in some frequency range, the associated Compton radiation will have a spectrum of the same slope, at a range of frequencies $\sim 3 \cdot 10^5(1+z)/H$ times higher. Fig. 4 shows the spectra for a source with the same properties as Fig. 1(a) at the present epoch ($z \sim 0$). If H is multiplied by k, say, but the radio properties of the source are kept the same, the inverse Compton spectrum moves to a frequency range k times lower, and its intensity, relative to that of the synchrotron radiation, decreases by a factor k^2. The 'second order' radiation is generally (but not always) negligible, and is not shown in the figure. The energy densities of the Compton and synchrotron radiation from a source would be equal for $H \sim 4 \cdot 10^{-6}(1+z)^2$ G. If the components of extended sources are receding from their parent object with velocities $v \sim c$ (Rees 1966; Ryle & Longair 1967), the Compton radiation is enhanced by a factor $\sim (1-v^2/c^2)^{-1}$ in total energy (for a given H), and is emitted in a frequency range $\sim (1-v^2/c^2)^{-1/2}$ higher.

If it were possible to measure the X-ray spectrum associated with an extended source, the magnetic field strength could be deduced—strong X-ray emission would imply a weak magnetic field. One could infer that the magnetic field was inhomogeneous if the Compton spectrum were restricted to a narrower range of

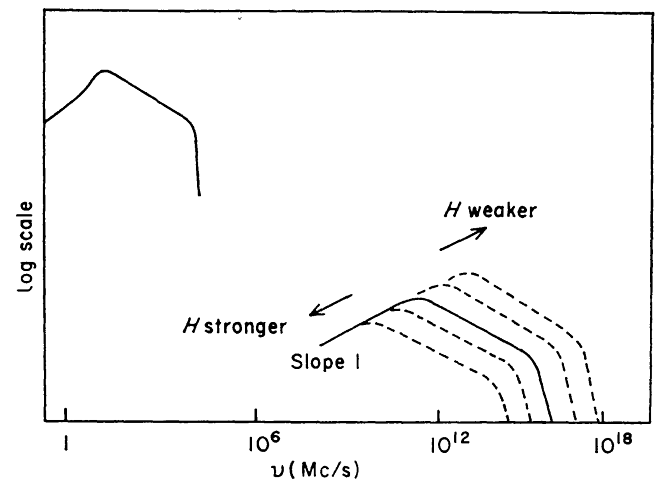


FIG. 4. *The spectrum of the radiation resulting from the scattering of the 3 °K black body radiation in a source with the same properties as that of Fig. 1(a). If the magnetic field strength were different, but the synchrotron spectrum remained the same, the associated Compton spectrum would alter in the manner indicated. A similar source at red-shift z would emit Compton radiation with a total power* $(1+z)^4$ *higher, in a frequency range* $(1+z)$ *higher.*

frequencies than the synchrotron spectrum, since this would imply that the spread of the synchrotron spectrum was not entirely due to a wide range of electron energies being present. In practice, X-rays would also arise from scattering of synchrotron radiation within the source, and it would be difficult to distinguish between these two components of the flux.

Sources with large z should emit X-rays more strongly than similar sources closer to us—a source like Cygnus A or Hercules A would probably be a powerful X-ray emitter if it were at a distance corresponding to $z \gtrsim 2$. However we would not necessarily expect very remote sources to be similar to those with small red-shifts, since many of the parameters which determine their properties will depend on epoch. The energy density of the background radiation is one such parameter; furthermore we know how it depends on z, at least in simple cosmological models, and so can estimate how the Compton effect will cause the properties of sources to depend on z.

The energy of the electrons which emit synchrotron radiation predominantly at frequencies $\sim \nu$ is $\sim m_0c^2(\nu/10^6H)^{1/2}$. These electrons will suffer synchrotron losses $\propto H^{3/2}$, and inverse Compton losses $\propto (1+z)^4H^{-1}$. Fig. 5 shows the lifetime of electrons radiating at $\sim \nu$, plotted as a function of z for different values of H. This represents an upper limit to the lifetime of the electrons in actual sources, where they will be subject to other losses (e.g. adiabatic losses). For a given value of H, the lifetime of the relevant electrons is nearly independent of red-shift unless z is so large that energy losses due to scattering of the primeval radiation become comparable with the synchrotron losses. For larger z the lifetime decreases $\propto (1+z)^{-4}$. There is a maximum lifetime for given z, (shown by the dashed line) which is proportional to $(1+z)^{-3}$, and is attained for a value of H such that $H^2/2\pi \sim$ the radiation energy density. The lifetime of electrons emitting synchrotron radiation at, say, 10^9 c/s in a source with $z \gtrsim 2$ must be $\lesssim 10^6$ yr.

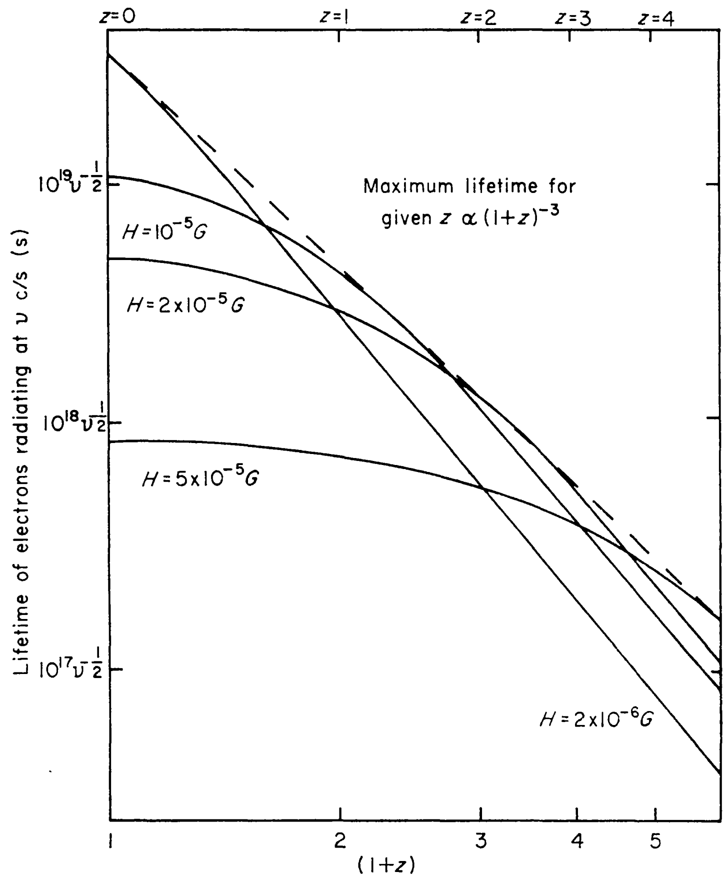


FIG. 5. *The lifetime of electrons emitting synchrotron radiation at a frequency ν as a function of the red-shift z of the source, assuming that the electrons are subject to synchrotron losses and to inverse Compton losses due to scattering of the primeval black body radiation. The curves are plotted for various values of the magnetic field strength H. The maximum lifetime at a given z is proportional to $(1+z)^{-3}$, and is attained for $H \sim 2 \cdot 10^{-6}(1+z)^2$ G.*

Two conclusions can be drawn from this:

(i) The curves shown in Fig. 5 determine (or at least set upper limits to) the lifetimes of extended sources within which the acceleration of electrons has ceased. The figure shows that, if $z \sim 0$, a source with $H \sim 2 \cdot 10^{-6}$ can have a longer lifetime than a source with $H \sim 2 \cdot 10^{-5}$ G, whereas the reverse is true for $z > 2$. There is probably a tendency for sources with low magnetic fields to be weaker, and so we can infer that strong sources have longer lifetimes, *relative to weak sources*, when z is large than they do at the present epoch.

(ii) In sources such as the halos of normal galaxies, which are continually being regenerated by the injection of relativistic electrons the individual electrons will tend to survive for a shorter time (and to radiate a larger fraction of their energy by the Compton effect) in remote sources than in those with $z \sim 0$. Distant sources of this type would thus be weaker radio emitters unless electrons were then injected at a much greater rate.

Both these conclusions are relevant to Longair's (1966) analysis of the radio source counts, according to which strong radio sources must have been more plentiful in the past, whereas the known limits on the extragalactic radio background imply that intrinsically weak sources could not have been proportionately more numerous.

5. *The X-ray background.* Various emission mechanisms, and many types of object, may be expected to contribute to the X-ray background in the universe. The fact that the spectrum of this radiation is observed to follow roughly a power law ($\propto \nu^{-\alpha}$ with $\alpha \sim 1$) between 10^3 and 10^6 eV indicates that a non-thermal contribution from relativistic electrons may dominate. Compton scattering of synchrotron radiation in radio sources (discussed in Section 3) could be the main contributer, but the intensity of the X-rays produced in this way depends so sensitively on the magnetic field strength and the degree of inhomogeneity in radio sources that we cannot even make an order of magnitude estimate of its importance. Felten & Morrison (1966) have considered whether the X-ray background could be due to Compton scattering of the primeval black body radiation by relativistic electrons, and have shown that the slope of the observed X-ray spectrum is consistent with this view. These authors considered a static universe filled with 3 degree black body radiation, and showed that, if the whole of the X-ray background were due to Compton scattering of this radiation, the relativistic electrons would have to move in a magnetic field $H \lesssim H_{\text{crit}} \sim 2 \cdot 10^{-7}$ G, since otherwise the associated synchrotron radiation would exceed the observed radio background intensity. They concluded that the X-rays could not be emitted by the electrons in active radio sources, but could be due to a much larger number of electrons which possibly escaped from defunct sources.

These conclusions should however, be modified to allow for the higher density of background radiation at large z in an evolving universe. H_{crit}—the upper limit on H if the electrons emitting the X-rays are not to produce too much radio background—must be defined as a function of z. In fact $H_{\text{crit}} \propto (1+z)^{3+\alpha/1+\alpha}$ (or roughly $H_{\text{crit}} \propto (1+z)^2$ since the spectral index $\alpha \sim 1$). Thus at $z \sim 2$, $H_{\text{crit}} \sim 2 \cdot 10^{-6}$ G, and at $z \sim 5$, $H_{\text{crit}} \sim 10^{-5}$ G. The magnetic field within weak or extended sources may well be as low as this. A large fraction of the observed radio background very probably comes from sources with $z \gtrsim 2$, and therefore these sources could contribute most of the X-ray background if their magnetic fields are $\lesssim 10^{-5}$ G. Alternatively the X-rays could come from even more distant objects ($z > 5$) in which the magnetic field has the strength typical of extended radio sources. These would not be observed as individual radio sources, and may not even make an appreciable contribution collectively to the radio background, because the relativistic electrons would radiate almost all their energy by the Compton effect.

6. *Conclusions.* A radio source emitting synchrotron radiation also emits an associated flux at higher frequencies by the inverse Compton effect. The spectrum

of this radiation has the form shown in Figs 1 and 2 for some simple cases. The intensity of the Compton radiation—which may exceed that of the synchrotron emission—is very sensitive to the assumed dimensions of the source and to the magnetic field strength. Since these quantities are very uncertain for quasars, we cannot estimate the intensity of their Compton radiation reliably. Nevertheless, if these objects are found to emit X-rays or γ-rays inverse Compton scattering is probably responsible. A high frequency flux would be expected from quasars if their optical continuum arises from Compton scattering of lower frequency radiation. (γ-rays may however form electron–positron pairs before they can escape from the source). The magnetic field within quasars, and the mechanism of their flux variations, could be inferred from observations of their high frequency emission. More extended sources also would emit an intense Compton-synchrotron flux if the magnetic field is weak, or if they have an inhomogeneous structure, and it is obviously important to establish the intensity of the X-ray emission from individual extragalactic sources. However the minimum X-ray flux detectable with present techniques is $\sim 10^{-10}$ ergs/cm^2/s, which is equivalent to a power of $\sim 10^{47}$ erg/s in a source with $z \sim 1$. Thus it may still be impossible to detect X-rays from quasars even if they are the dominant form of emission (in terms of energy output) from these objects. Compton scattering of the primeval black body radication (if it exists) could give rise to X-ray emission from extended sources. These X-rays would tend to be stronger, relative to the radio emission, in sources with large z. The Compton losses set a limit $\propto (1+z)^{-3}$ to the lifetime of relativistic electrons emitting synchrotron radiation at a given frequency, and this limit could exert an influence on the evolution of remote sources. The observed X-ray background could be mainly due to the integrated contribution from distant extragalactic sources.

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