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RELIC SOURCES AND DIFFUSE CLUSTER RADIO EMISSION

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ABSTRACT

Late evolution of an extended radio source is studied in the context of a simple model of magnetically driven expansion. The evolving radio spectrum is calculated by accounting for synchrotron, Compton, and expansion energy losses of relativistic electrons in the varying magnetic field of the source. We estimate the Compton X-ray fluxes of the relics 0924+30 and 1253+275, and conclude that the latter source is likely to be a dominant component of the high-energy flux from the Coma region, if measured by a detector with a large field of view (such as the OSSE on board the *Compton Gamma Ray Observatory*). We briefly discuss the possibility that steep-spectrum relics and diffuse radio sources in clusters have a common origin.

Subject headings: intergalactic medium — radiation mechanisms: nonthermal — radio continuum: galaxies

1. INTRODUCTION

In its late evolutionary stage, an extended radio lobe enters the realm of intergalactic (IG) phenomena; therein lies the interest in its continued exploration. Following the termination of energy supply by a central nucleus, the magnetic-pressure–driven expansion results in a gradual decrease of its radio emission and eventual fading. While it would seem that the interest in the dying radio source should also fade away, the transfiguration of the source into an IG entity is the key to salvation from oblivion: IG phenomena are typically weak, but the useful virtue of the fading lobe—a relic—is in its relatively known (by means of analogy with currently active radio sources) past properties, which serve as initial data in the quantitative description of its evolution. Of particular interest is the evolution of the spectrum, whose exact features can potentially be used to probe the IG medium, and even more so the intracluster (IC) environment.

During the late evolutionary stage the spectra of extended radio sources steepen due to synchrotron and Compton energy loss processes; convex spectra are expected. Detections of diffuse, steep-spectrum relics are relatively recent (Cordey 1987; Goss et al. 1987; Giovannini, Feretti, & Stanghellini 1991; Dewdney et al. 1991; Harris et al. 1993), probably reflecting the fact that the characteristic timescale of evolution is relatively short, of the order of a few times 10^8 yr (Cordey 1986 and § 2 below). At present only four relics are identified, a very small number when compared to the size of the parent population of extended lobes. Their typical spatial extent is in the range of several hundred kpc, radio luminosities vary from 5×10^{40} to 4×10^{41} ergs s^{-1} (i.e., are comparable to the typical cluster halo luminosity), and equipartition magnetic fields are of the order of 1 μG (see § 5 of this paper).

Besides the intrinsic interest in a complete description of the evolution of radio sources, we can—in principle—gain some insight on the properties of the medium in which they expand, the elusive IG medium. For example, if expansion of the source stops when the internal magnetic pressure equals that in the medium, then we will perhaps be able to determine the pressure of the IG gas. Taking $B_{min} = 0.1$ μG to the weakest field that can still be realistically determined by measurements of synchrotron emission, it follows that deductions regarding the IG gas can be relevant only if its density is higher than $\sim 3 \times 10^{-7}$ T_7 cm^{-3}, where T_7 is the gas temperature in units of 10^7 K.

Of particular interest is the possible relation between radio relics and diffuse steep-spectrum sources in clusters of galaxies, of which Coma C—the extended ~ 1 Mpc source in the central region of the Coma cluster—is the best-studied, "typical" example. The origin of the diffuse IC radio emission has not yet been uniquely determined (see Rephaeli 1988 for a brief review); among other possibilities, it has been suggested (Harris & Miley 1978) that cluster sources are the expanded remnants of radio galaxies. The study of relics may be important for resolution of the issue of the origin of IC radio emission, as discussed in § 4 below.

Relics can also be diagnosed by X-rays: Compton scattering of the electrons (relativistic, unless otherwise specified) off the cosmic microwave background (CMB) yields photons of energy ≥ 1 keV. The low-energy X-ray emission may be detectable from nearby relics, if not in clusters (where thermal emission from the IC gas dominates at energies below 20–30 keV). This would yield values of the electron energy density and magnetic field based only on observables.

These and other considerations motivate our interest in relics. Our treatment here is in the context of a simple model for the evolution of the source, but the ensuing spectral changes are calculated exactly, taking all relevant energy loss mechanisms into account.

2. LATE EXPANSION OF A RADIO LOBE

Expansion of a radio lobe begins early, from the time of its ejection from a central active region. Here we focus on the late expansionary phase which begins when the lobe is no longer supplied with energy by the central nucleus. The expansion, which is driven primarily by the magnetic pressure force, stops only when the internal pressure within the relic equals that of the IG gas. The IG gas pressure is unknown, so it is possible that the relic does not stop expanding before it disperses and completely fades away. Here we give a simple treatment of the late expansion, taking some fiducial magnetic field, internal gas density, and radius of the lobe at some initial time which marks the end of the period during which the nuclear active region supplies energy to the lobe. Our intuitive approach here is justified by the lack of detailed observational information on exact conditions within the lobe; thus a more elaborate treatment is not warranted at present.

Consider a spherically symmetric radio lobe region expanding into IG space whose pressure is (at least initially) low in comparison with $B^2/8\pi$ in the source. This may be not the case of the cores of rich clusters; expansion of a radio lobe in the IC space is discussed in § 4. Introducing an effective radius, $R(t)$, of the relic at time t after the initial time, gas mass density $\rho(t)$, and magnetic field $B(t)$, we can write the expansion equation as

$$\rho \frac{d^2R}{dt^2} = -\frac{d}{dR}\left(\frac{B^2}{8\pi}\right) . \tag{1a}$$

We ignore self-gravity of the lobe and its gas pressure; this is reasonable under typical conditions assumed here. We also note that due to the low density of the intergalactic gas, the dynamical effect of the ambient mass swept up by the supersonically expanding front of the radio lobe can be ignored (as is argued below).

We use a nondimensional radial variable x defined in terms of the radius at the initial time, R_0, i.e., $x = R/R_0$; clearly, $\rho = \rho_0/x^3$, and from flux conservation (in the highly conducting lobe medium) $B = B_0/x^2$. The nondimensional time (in units of the initial expansion time) is $\tau = tV_A/R_0$, $V_A = B_0(4\pi\rho_0)^{-1/2}$ is the Alfvén velocity. The nondimensional analog of equation (1a) is

$$\frac{d^2x}{d\tau^2} = \frac{2}{x^2} . \tag{1b}$$

Equation (1b) can easily be integrated once the initial conditions are specified. Obviously, at $\tau = 0$ we have $x = 1$; less obvious is an initial condition of $dx/d\tau$, because the lobe had been expanding before the energy supply was turned off. Our choice of an initial value of $dx/d\tau$ at $\tau = 0$ is based on the following consideration: if the lobe had been expanding for some time before the energy supply was cut off, the equation (1a) describes the earlier evolution as well. That first phase began with $dx/d\tau = 0$, and very quickly the nondimensional velocity reached its limiting value of 2 (i.e., $dR/dt = 2V_A$). Therefore, we may use $dx/d\tau = 2$ at $\tau = 0$ for illustrative purposes, realizing that all the following general results are valid for any $\tau(x)$ which might be determined in a more detailed expansion model.

With these initial conditions, the solution of equation (1b) is

$$\tau = \frac{1}{4\sqrt{2}}\left\{[2x(2x-1)]^{1/2} - \sqrt{2} + \ln\left[\frac{(2x)^{1/2} + (2x-1)^{1/2}}{1+\sqrt{2}}\right]\right\} ; \tag{2}$$

this function is shown in Figure 1. A characteristic expansion time is

$$t_0 = R_0/V_A = 1.1 \times 10^7 B_{-4}^{-1} N_{-2}^{1/2} R_{30} \text{ yr} , \tag{3}$$

where B_{-4} is the *initial* magnetic field in units of 10^{-4} G, N_{-2} is the *initial* number density of the ionized gas component in the source in units of 10^{-2} cm^{-3}, and R_{30} is the *initial* size of the source in units of 30 kpc. The fiducial value for the magnetic field corresponds to a rather powerful radio galaxy (see the review by Miley 1980, who gives a range of equipartition B of 10^{-5} to 10^{-3} G; we obviously assume that only powerful radio galaxies comprise the parent population of relics, otherwise the latter would become undetectable too early). A lobe radius of 30 kpc is typical for a compact radio source; $N = 10^{-2}$ cm^{-3} yields quite a reasonable total ionized gas mass of $M_{gas} \approx 2.7 \times 10^{10}$ $M_\odot$. With these characteristic values, $V_A(x) = B(x)[4\pi\rho(x)]^{-1/2} \approx 2230$ $x^{-1/2}$ km s^{-1}, and the total magnetic field energy is $E_{mag} \approx 1.3 \times 10^{60}/x$ ergs.

A rough estimate of the radius of the source when the external pressure stops the expansion can be obtained by requiring that the IG gas pressure be equal to $B^2/8\pi$. The parameters of the IG gas are unknown, but, as we shall immediately see, the result depends on them only weakly. Merely as an illustration, we take $N_{ig} = 3 \times 10^{-7}$ cm^{-3}, a value which corresponds to 0.1 of the cosmological

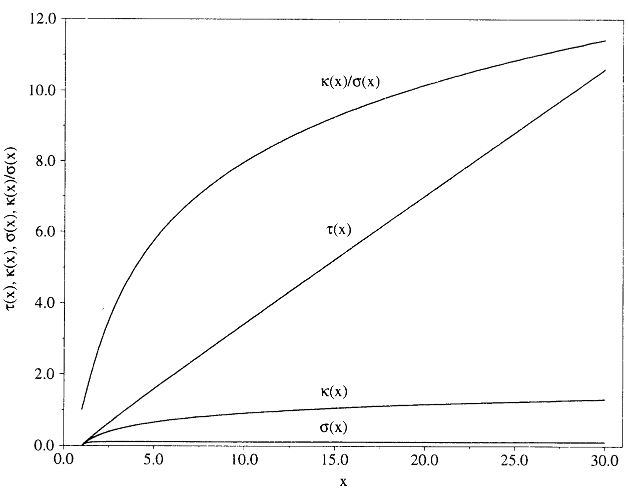

FIG. 1.—Plotted are functions $\tau(x)$ (eq. [2]), $\kappa(x)$, $\sigma(x)$ (eq. [7]), and $c_S B_0^2 \omega(x) = \kappa(x)/\sigma(x)$ (eq. [8])

closure density (for a Hubble constant of 50 km s^{-1} Mpc^{-1}), and, somewhat arbitrarily, $T_{ig} = 10^7$ K. For this choice of N_{ig} and T_{ig}, the influence of the IG medium is significant while the relic is still detectable (see § 1). These values are consistent with the *COBE*/FIRAS upper limit of 2.5×10^{-5} (Mather et al. 1994) on the Comptonization parameter. The final expansion factor is then (k is the Boltzmann constant)

$$x_f = \left(\frac{B_0^2}{8\pi N_{ig} k T_{ig}}\right)^{1/4} \approx 31 B_{-4}^{1/2}\left(\frac{N_{ig}}{3 \times 10^{-7}\ \mathrm{cm}^{-3}}\right)^{-1/4}\left(\frac{T_{ig}}{10^7\ \mathrm{K}}\right)^{-1/4} . \tag{4}$$

For the adopted fiducial values of the parameters, the relic will expand to a size of almost 1 Mpc, and the total expansion time is $\sim 11.0 t_0 \approx 1.2 \times 10^8$ yr. Note that for these characteristic values the swept-up mass is only $M_{ig} \approx 2.3 \times 10^9\ M_\odot\ \mathrm{Mpc}^{-3}$, about a factor of 10 lower than the ionized gas mass in the lobe.

3. EVOLUTION OF THE SYNCHROTRON AND COMPTON SPECTRA

The commonly used expressions of the Compton-synchrotron spectra apply when the source does not expand, and the magnetic field does not vary over times comparable to or shorter than a characteristic synchrotron loss time. In what follows we shall discuss steepening of the source spectrum during expansion of the source. Our treatment differs from the "standard" case of spectral evolution due to the evolving electron energy distribution as a result of energy losses (e.g., Pacholczyk 1970) in that the magnetic field also varies with time. The variation of B has to be taken into account, since the synchrotron loss time for a GeV electron in a 10 μG magnetic field is comparable to the duration of the expansion. Our treatment here is also more general as we include Compton losses which are usually ignored in the case of radio galaxies because of their strong magnetic fields; here, however, the field weakens with time.

There are currently two models for the evolution of electron energy spectra, depending on whether there is continuous isotropization of the electron distribution in pitch angles. If efficient, isotropization should lead to a more abrupt decline of the radiation intensity at high frequencies. Some observations are better fitted by the model without isotropization, although the steepening may be masked owing to the random nature of the magnetic field within a source (Tribble 1993).

Usually the so-called Jaffe-Perola (JP; Jaffe & Perola 1973) model of continuous isotropization is preferred, where relativistic electrons excite Alfvén waves due to their streaming motion along the magnetic field, and the waves, in turn, scatter the electrons and isotropize the distribution. In this picture it is explicitly or implicitly assumed that the electrons stream from a central source, and thus their distribution is intrinsically anisotropic, so Alfvén waves can be excited. However, we deal with a source where the central engine is dead already, and the (isotropized) distribution of electrons is uniform in space. Under these conditions it is unclear whether Alfvén waves can be excited and isotropize the electron distribution, and whether the JP model should be viewed as more realistic than the so-called Kardashev-Pacholczyk (KP; see Pacholczyk 1970 and references therein) model, in which the pitch angle does not change. Note that the distribution will become anisotropic with time due to synchrotron losses, but such an anisotropy does not lead to growth of Alfvén waves.

For completeness we present below results for both models. However, we shall see that Compton losses (which are neglected in more conventional cases) deplete the population of high-frequency emitting electrons even without isotropization (in accordance with Tribble's 1993 numerical results). Thus, while there is some uncertainty regarding the more appropriate representation of the electron pitch-angle distribution, the KP model leads to more conservative conclusions in the case of relics. In this regard, note that Tribble's (1993) arguments concerning the random nature of the magnetic field are somewhat irrelevant here, because, as he showed numerically, Compton losses lead to a cutoff even in a random field. In fact, the assumption that the field is random introduces only a factor close to unity into the cutoff frequency.

3.1. *Energy Spectrum of Relativistic Electrons*

Compton, synchrotron, and expansion energy losses of a relativistic electron in an expanding radio source yield a total loss rate

$$\frac{dE}{d\tau} = -\xi t_0 (1 + c_S B_0^2 x^{-4} \sin^2\theta) E^2 - \frac{E}{x}\frac{dx}{d\tau} , \tag{5}$$

where $\xi = 1.6 \times 10^{-14}$ ergs^{-1} s^{-1}, $c_S = 10^{11}$ in c.g.s. units, and θ is the electron's pitch angle. The first term on the right-hand side of this equation is the loss rate of an electron which is Compton-scattered off the cosmic microwave background radiation. (We ignore the dependence on redshift because of the short lifetime of relics, and because only the nearby ones are detectable.) The second term expresses the synchrotron loss rate, and the third term describes expansion losses. Integration (after transforming from τ to x, and substituting $E = E'/x$) yields

$$E = \frac{E_0/x}{1 + \xi t_0[\kappa(x) + c_S B_0^2 \sigma(x) \sin^2\theta]E_0} , \tag{6}$$

where

$$\kappa(x) = \int_1^x \frac{1}{x}\frac{d\tau(x)}{dx}\,dx = \frac{1}{\sqrt{2}} \ln\left[\frac{(2x)^{1/2} + (2x-1)^{1/2}}{1+\sqrt{2}}\right] ,$$

$$\sigma(x) = \int_1^x \frac{1}{x^5}\frac{d\tau(x)}{dx}\,dx = \frac{[x(2x-1)]^{1/2}(5 + 12x + 32x^2 + 128x^3) - 177x^4}{35x^4} . \tag{7}$$

The integrals are evaluated with $\tau(x)$ from equation (2); see Figure 1. We shall also introduce

$$\omega(x) = \frac{1}{c_S B_0^2} \frac{\kappa(x)}{\sigma(x)} , \tag{8}$$

which obeys $\omega(x) \ll 1$; e.g., if $B_0 = 10^{-4}$ G, then $\omega(x) = O(10^{-3})$; see Figure 1. The function $\omega(x)$ is essentially a measure of the relative importance of Compton and synchrotron losses over the period from $\tau = 0$ to $\tau = \tau(x)$. Its small value is due to the initially high magnetic field and the dominance of synchrotron losses. Obviously, $\kappa(x)$ and $\sigma(x)$ are model-dependent, but their ratio cannot be expected to be very large. Therefore, $\omega(x) = O(1)$ only if B_0 is relatively small ($\sim 3 \times 10^{-5}$ G), but this case is of no interest to us (see the discussion above).

Now suppose we start from a power-law distribution of electrons,

$$n(E_0, \theta, x = 1)dE_0 = n_0(1)E_0^{-p}\, dE_0 , \tag{9}$$

At a time corresponding to size x, and assuming that there is no isotropization (KP case), we have

$$n(E, \theta, x)dE = n_0(x)x^{1-p}E^{-p}\{1 - \xi t_0 c_S B_0^2 x\sigma(x)E[\omega(x) + \sin^2\theta]\}^{p-2}dE = n_0(x)x^{1-p}E^{-p}\left\{1 - \frac{E}{E_1}[\omega(x) + \sin^2\theta]\right\}^{p-2} dE , \tag{10a}$$

where E_0 and dE_0 are changed to E and dE (using eq. [6]). If the pitch-angle distribution is isotropic (JP case), then $\langle \sin^2\theta \rangle = \frac{2}{3}$, and with $\omega(x) \ll 1$ we have

$$n(E, \theta, x)dE = n_0(x)x^{1-p}E^{-p}\left(1 - \frac{2}{3}\frac{E}{E_1}\right)^{p-2} dE . \tag{10b}$$

The characteristic energy E_1 equals $[\xi t_0 c_S B_0^2 x\sigma(x)]^{-1} \approx 0.12 B_{-4}^{-1} N_{-2}^{-1/2} R_{30}^{-1}[x\sigma(x)]^{-1}$ GeV.

Equations (10a) and (10b) describe the electron energy distribution for energies below some critical value, at which the right-hand sides vanish; above this cutoff energy, $n(E, \theta, x) = 0$. Thus, at a time corresponding to size x there will be no electrons with energy higher than $E_c = E_1/\omega(x) \approx 120 B_{-4} N_{-2}^{-1/2} R_{30}^{-1}[x\kappa(x)]^{-1}$ GeV in the KP case, or than $E_c = (3/2)E_1 \approx 0.18 B_{-4}^{-1} N_{-2}^{-1/2} R_{30}^{-1}[x\sigma(x)]^{-1}$ GeV in the JP case.

Integrating equations (10a) and (10b) over θ (as can readily be seen, in the first case we have to take account only of small pitch angles, such that $\sin^2\theta < E_1/E - \omega(x)$; electrons with large θ lose their energy very fast), we obtain

$$n(E, x) = \begin{cases} 4\pi n_0(x)x^{1-p}E^{-p} , & E \ll E_1 , \\ \dfrac{2\pi n_0(x)}{p-1} x^{1-p}E_1 E^{-(p+1)}\left(1 - \dfrac{E}{E_c}\right)^{p-1} , & E_1 \ll E \le E_c , \\ 0 , & E_c < E \end{cases} \tag{11a}$$

(KP case), and

$$n(E, x) = 4\pi n_0(x)x^{1-p}E^{-p}\left(1 - \frac{2}{3}\frac{E}{E_1}\right)^{p-2} \tag{11b}$$

(JP case). The normalization factor $n_0(x)$ can be found by requiring that the total number of electrons be conserved during the expansion. The exact dependence $n_0(x)$ is nontrivial because integration over energies is involved (with the lowest possible energy also depending on x); however, this dependence will be irrelevant to the discussion below. For a given value of x the energy distributions are shown schematically in Figure 2.

3.2. *Radio Spectrum*

The radio (spectral energy) flux from the expanding source at a distance D is given in the following general expression (e.g., Pacholczyk 1970):

$$F_S(\nu) = \frac{(4\pi)^2}{3} c_3 R_0^3 D^{-2} B_0 x \int_0^{\pi/2} d\theta \sin^2\theta \int_0^{E_c} dE\, \mathscr{F}(z) n(E, \theta, x) , \tag{12}$$

where

$$\mathscr{F}(z) = z \int_z^{\infty} dz_1 K_{5/3}(z_1) , \qquad z = \frac{\nu x^2}{c_1 B_0 \sin\theta E^2} , \tag{13}$$

$c_1 = 3e/(4\pi m^3 c^5)$, and $c_3 = \sqrt{3}\, e^3/(4\pi m c^2)$.

The flux $F_S(\nu)$ can be expressed in approximate closed forms in the following limits:

1. At low frequencies, $\nu \ll \nu_1 = c_1 B_0 E_1^2/x^2$, emitted primarily by low-energy electrons for which radiative losses are not important, we have (in both the KP and JP cases)

$$F_S(\nu) = \frac{8\pi^2}{3} c_1^{(p-1)/2} c_3 c_8(p) c_9(p) R_0^3 D^{-2} B_0^{(p+1)/2} n_0(x) x^{3-2p} \nu^{(1-p)/2} , \tag{14}$$

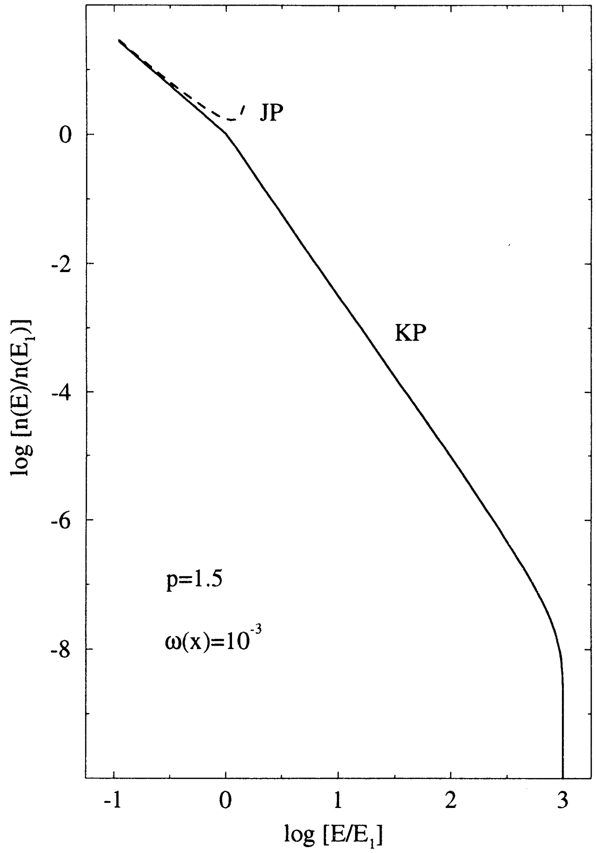

FIG. 2.—Plotted are normalized electron energy distributions in the KP (eq. [11a], *solid line*) and JP (eq. [11b], *dashed line*) cases; $p = 1.5$ and $\omega(x) = 10^{-3}$ are assumed.

where

$$c_8(p) = \int_0^\infty z^{(p-3)/2}\mathscr{F}(z)dz \ , \qquad c_9(p) = \int_0^{\pi/2} (\sin\,\theta)^{(p+3)/2}d\theta$$

(these functions are tabulated in Pacholczyk 1970).

2. At intermediate frequencies, $\nu_1 \ll \nu \ll \nu_c = \nu_1/\{16[\omega(x)/3]^{3/2}\}$, emitted by electrons that lose a significant fraction of their energy in synchrotron emission during the expansion, we have in the KP case

$$F_S(\nu) = \frac{8\pi^2}{3}\, c_1^{(p-1)/2} c_3\, c_{10}(p) c_{11}(p) R_0^3 D^{-2} B_0^{(p+1)/2} n_0(x) x^{3-2p} \nu_1^{(p+5)/6} \nu^{-(2p+1)/3} \ , \tag{15}$$

where

$$c_{10}(p) = \int_0^\infty z^{2(p-1)/3}\mathscr{F}(z)dz \ , \qquad c_{11}(p) = \int_0^1 u^{(p+3)/2}(1-u^{3/2})^{p-2}du$$

(see Pacholczyk 1970 again).

In the JP case in this frequency range ($\nu \gg \nu_1$) the spectrum has an exponential cutoff:

$$F_S(\nu) = \left(\frac{3}{2}\right)^{p-2} 2\pi^3 c_1^{p-1} c_3\, c_c(p) R_0^3 D^{-2} B_0^{(p+1)/2} n_0(x) x^{3-2p} \nu_1^{(p-1)/2} \nu^{1-p} \exp\left(-\frac{4\nu}{9\nu_1}\right) , \tag{16}$$

where

$$c_c(p) = \frac{\Gamma[p/2]\Gamma[(p-1)/2]}{\pi^{1/2}} + \frac{\Gamma[p-1]}{2^{p-2}} \ .$$

3. In the KP case we must consider also emission at high frequencies ($\nu \gg \nu_c$), emitted primarily by high-energy electrons, which are subject to significant Compton losses,

$$F_S(\nu) = \frac{(4\pi)^3}{4^p 3\sqrt{6}} c_1^{(p-1)/2} c_3\, c_c(p) R_0^3 D^{-2} B_0^{(p+1)/2} n_0(x) x^{3-2p} \left[\frac{\omega(x)}{3}\right]^{(4-p)/2} \nu_1^{(p-1)/2} \times \nu^{1-p} \exp\left\{-16\left[\frac{\omega(x)}{3}\right]^{3/2} \frac{\nu}{\nu_1}\right\}. \quad (17)$$

Note that the above are general results, applicable also in other source expansion models with the function $\tau(x)$ assuming different forms than the above.

The random field case deserves a special note here. One can show (see, e.g., Tribble 1993 for numerical results) that the KP spectrum is insignificantly changed if B is assumed random. Indeed, the JP spectrum in the intermediate-frequency region will be practically indistinguishable from the KP one, but there will still be an exponential cutoff at high frequencies. The cutoff is due to Compton losses, which deplete the population of high-energy electrons independently of the magnetic field; this is a general feature of the synchrotron spectrum of a relic.

The overall normalized spectrum in the KP case can be obtained by matching the three approximate results (14), (15), and (17) at $\nu = \nu_1$ and $\nu = \nu_c$ for a given x. It is

$$\frac{F_S(\nu)}{F_S(\nu_1)} = \begin{cases} \left(\dfrac{\nu}{\nu_1}\right)^{(1-p)/2}, & \nu < \nu_1\,, \\ \left(\dfrac{\nu}{\nu_1}\right)^{-(2p+1)/3}, & \nu_1 < \nu < \nu_c\,, \\ \left(\dfrac{\nu_1}{\nu_c}\right)^{(4-p)/3} \left(\dfrac{\nu}{\nu_1}\right)^{1-p} \exp\left(\dfrac{\nu_c - \nu}{\nu_c}\right), & \nu_c < \nu\,. \end{cases} \quad (18a)$$

Matching equations (14) and (16) at ν_1, we get the approximate normalized spectrum for the JP case:

$$\frac{F_S(\nu)}{F_S(\nu_1)} = \begin{cases} \left(\dfrac{\nu}{\nu_1}\right)^{(1-p)/2}, & \nu < \nu_1\,, \\ \left(\dfrac{\nu}{\nu_1}\right)^{1-p} \exp\left[\dfrac{4(\nu_1 - \nu)}{9\nu_1}\right], & \nu_1 < \nu\,. \end{cases} \quad (18b)$$

The two spectra (eqs. [18a] and [18b]) are schematically drawn in Figure 3.

The break and cutoff frequencies are $\nu_1 \approx 20 B_{-4}^{-1} N_{-2}^{-1} R_{30}^{-2} [x^2 \sigma(x)]^{-2}$ MHz and $\nu_c \approx 200 B_{-4}^2 N_{-2}^{-1} R_{30}^{-2} [x^4 \sigma^{1/2}(x) \kappa^{3/2}(x)]^{-1}$ GHz, respectively. These frequencies decrease with time. When the pressure of the IG medium stops the expansion, the qualitative picture does not change, although ν_1 and ν_c shift toward low frequencies at a smaller rate (as the magnetic field attains a constant limiting value).

3.3. *Compton X-Ray Spectrum*

The Compton X-ray (photon) flux of an expanding relic can be written in the following form:

$$f_C(\epsilon) = \frac{8}{3} \frac{\alpha^2}{\hbar m c^2} R_0^3 D^{-2} x^3 \int_0^\infty \frac{d\epsilon_0}{\epsilon_0} \int_0^\infty \frac{dE}{E} N_{\rm ph}(\epsilon_0) \mathscr{G}(q) n(E, x) \quad (19)$$

(see, e.g., Blumenthal & Gould 1970). Here $N_{\rm ph}(\epsilon_0)$ is the CMB blackbody spectrum, $N_{\rm ph}(\epsilon_0) = \epsilon_0^2/[\pi^2 \hbar^3 c^3 (e^{\epsilon_0/kT} - 1)]$ at temperature T; $\alpha = e^2/(\hbar c)$ is the fine-structure constant, and $n(E, x)$ is given by equation (11a) or (11b), depending on the exact model. The function $\mathscr{G}(q)$ is the scattered photon distribution in the Thomson limit, $\mathscr{G}(q) = 2q \ln q + (1 + 2q)(1 - q)$, and $q = \epsilon(4\gamma^2 \epsilon_0)$, where $\gamma = E/(mc^2)$ and ϵ is the energy of the scattered photon. [Recall that from the kinematics of Compton scattering, $1/4\gamma^2) \le q \le 1$.]

Again we can derive approximate expressions in the following cases:

1. At low energies [$\epsilon \ll \epsilon_1 = 4\gamma_1^2 kT$, $\gamma_1 = E_1/(mc^2)$] the result in both models is

$$f_C(\epsilon) = 2^{p+4} \frac{\pi}{3} d_1(p) d_2(p) \frac{\alpha^2}{\hbar (mc^2)^{p+1}} R_0^3 D^{-2} n_0(x) x^{4-p} (kT)^{(p+4)/2} (\epsilon')^{-p/2}\,, \quad (20)$$

where

$$d_1(p) = \int_0^1 q^{(p-2)/2} \mathscr{G}(q) dq\,, \qquad d_2(p) = \int_0^\infty \frac{u^{(p+2)/2}}{e^{u/kT} - 1} du\,.$$

2. At intermediate energies [$\epsilon_1 \ll \epsilon \ll \epsilon_c = 4\gamma_c^2 kT$, $\gamma_c = E_c/(mc^2)$] the KP model gives

$$f_C(\epsilon) = \frac{2^{p+3}\pi}{3(p-1)} d_3(p) d_4(p) \frac{\alpha^2}{\hbar (mc^2)^{p+1}} R_0^3 D^{-2} n_0(x) x^{4-p} (kT)^{(p+5)/2} \gamma_1(\epsilon)^{-(p+1)/2}\,, \quad (21)$$

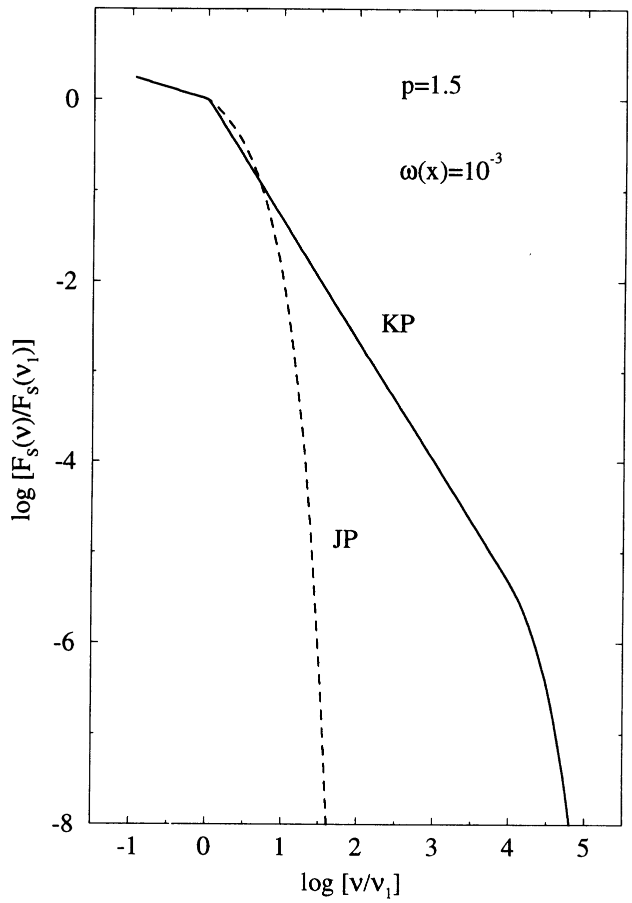

FIG. 3.—Plotted are normalized synchrotron spectra in the KP (eq. [18a], *solid line*) and JP (eq. [18b], *dashed line*) cases; $p = 1.5$ and $\omega(x) = 10^{-3}$ are assumed

where

$$d_3(p) = \int_0^1 q^{(p-1)/2}\mathscr{G}(q)dq\ , \qquad d_4(p) = \int_0^\infty \frac{u^{(p+3)/2}}{e^{u/kT} - 1}\, du\ .$$

Note that although the Compton spectrum obeys a power law, the index is different from that of the synchrotron emission. It is important to realize that the two power-law indices are equal only at steady state.

The JP case gives an exponential cutoff at energies $\epsilon \gg \epsilon_1$:

$$f_C(\epsilon) = 2^{p+4}3^{p-3}\pi c_c(p)\, \frac{\alpha^2}{\hbar(mc^2)^{p+1}}\, R_0^3 D^{-2} n_0(x)x^{4-p}(kT)^{p+1}\gamma_1^p \epsilon^{1-p} \exp\left(-\frac{4\epsilon}{9\epsilon_1}\right) . \tag{22}$$

This result does not, of course, depend on whether the magnetic field is regular or random.

3. In the KP case there is also an exponential cutoff at high energies ($\epsilon \gg \epsilon_c$):

$$f_C(\epsilon) = \frac{4^{p+1}\pi}{3}\, c_c(p)\, \frac{\alpha^2}{\hbar(mc^2)^{p+1}}\, R_0^3 D^{-2} n_0(x)x^{4-p}\gamma_1\gamma_c^{p-1}(kT)^{p+2}\epsilon^{-p} \exp\left(-\frac{\epsilon}{4\gamma_c^2 kT}\right) . \tag{23}$$

It is convenient to present the Compton spectrum for a given x in a normalized form, matching the approximate results in the three regions. In the KP case the overall spectrum is

$$\frac{f_C(\epsilon)}{f_C(\epsilon_1)} = \begin{cases} \left(\dfrac{\epsilon}{\epsilon_1}\right)^{-p/2} , & \epsilon < \epsilon_1\ ; \\ \left(\dfrac{\epsilon}{\epsilon_1}\right)^{-(p+1)/2} , & \epsilon_1 < \epsilon < \epsilon_c\ ; \\ \left(\dfrac{\epsilon_c}{\epsilon_1}\right)^{(p-1)/2}\left(\dfrac{\epsilon}{\epsilon_1}\right)^{-p} \exp\left(\dfrac{\epsilon_c - \epsilon}{\epsilon_c}\right) , & \epsilon_c < \epsilon\ . \end{cases} \tag{24a}$$

In the JP case we get

$$\frac{f_C(\epsilon)}{f_C(\epsilon_1)} = \begin{cases} \left(\dfrac{\epsilon}{\epsilon_1}\right)^{-p/2}, & \epsilon < \epsilon_1 ; \\ \left(\dfrac{\epsilon}{\epsilon_1}\right)^{-p} \exp\left[\dfrac{4(\epsilon_1 - \epsilon)}{9\epsilon_1}\right], & \epsilon_1 < \epsilon . \end{cases} \tag{24b}$$

The spectra (eqs. [24a] and [24b]) are schematically shown in Figure 4. The two characteristic photon energies are $\epsilon_1 = 5.2 \times 10^{-2} B_{-4}^{-2} N_{-2}^{-1} R_{30}^{-2} [x\sigma(x)]^{-2}$ keV and $\epsilon_c = 5.2 \times 10^4 B_{-4}^{2} N_{-2}^{-1} R_{30}^{-2} [x\kappa(x)]^{-2}$ keV. Both ϵ_1 and ϵ_c decrease with time. The detection of Compton radiation from a relic can potentially resolve the issue of isotropization in favor of the KP model.

4. EXTENDED INTRACLUSTER SOURCES: RELICS?

The origin of relativistic electrons and magnetic fields in clusters of galaxies is not completely known. Harris et al. (1993) noted the similarities between the characteristics of four relics and those of the diffuse emission in the Coma cluster. Is it likely that Coma C and other diffuse cluster radio sources are remnants of powerful radio sources?

First, let us estimate how strong the magnetic field in the progenitor radio source must be to produce a Coma-like emission. The current lower limit on the IC field in Coma is 0.1 μG (Rephaeli, Ulmer, & Gruber 1994; Rephaeli & Goldshmidt 1992), but there are good indications that IC fields are typically several times stronger (Goldshmidt & Rephaeli 1993). To account for an 0.5 μG field over a region of 0.5 Mpc radius, a 30 kpc source must have had a rather strong, but not too unusual, magnetic field, $B_0 \sim 1.4 \times 10^{-4}$ G. Even somewhat stronger fields are not excluded in radio galaxies (Miley 1980). The equipartition magnetic field energy in Coma is $\sim 1.3 \times 10^{60}$ ergs, so that in the 30 kpc progenitor the total magnetic field energy was $\sim 2.2 \times 10^{61}$ ergs, corresponding to $B_0 \approx 4 \times 10^{-4}$ G. Such a large energy may seem rather extreme but in fact may explain why cluster sources are quite rare.

The magnetic field pressure in the radio source can easily overcome IC gas pressure during the early expansion phase (with $N \sim 3 \times 10^{-3}$ cm^{-3} and $T \sim 10^8$ K, the thermal gas pressure corresponds to a magnetic field of only $B \sim 32$ μG), although the characteristic expansion time will probably be somewhat longer than estimated above. However, it is difficult to explain how cluster sources dispersed to their present extents, because the gas pressure is now much higher than the magnetic pressure. It seems

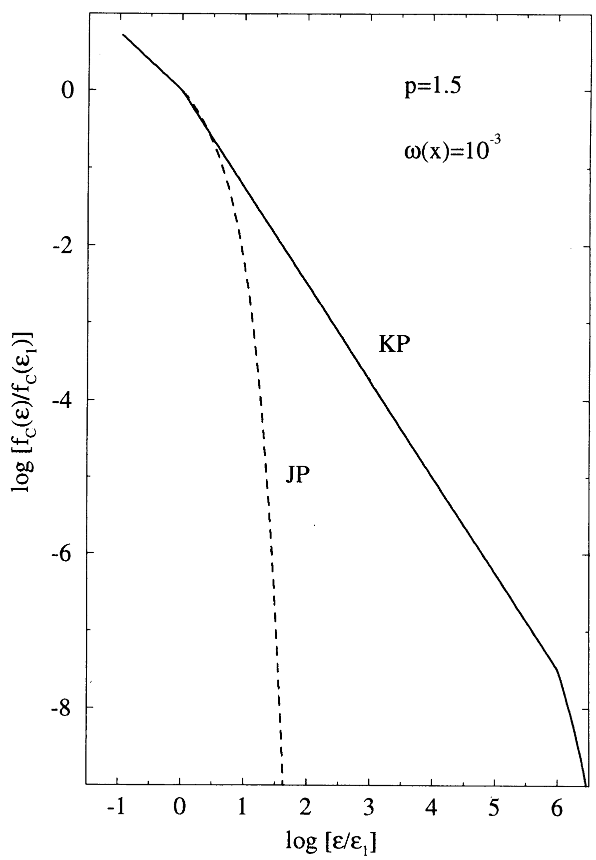

FIG. 4.—Plotted are normalized Compton spectra in the KP (eq. [24a], *solid line*) and JP (eq. [24b], *dashed line*) cases; $p = 1.5$ and $\omega(x) = 10^{-3}$ are assumed

necessary that the progenitor source had been dispersed before the gas was heated up to its present temperature, or else that most of the expansion had occurred before the gas accumulated in the IC space. In either case, it would seem unlikely that diffuse IC sources survived for such a long time (a few billion years), because electrons would have had to endure heavy Compton-synchrotron losses. Processes like ram pressure, or gas-mixing due to galactic motions, could perhaps manage to disperse the magnetic field over the IC space, although these processes would also have taken a very long time.

Is it possible to use cluster halo spectra to test the hypothesis that cluster sources are dispersed relics? So far, high-frequency observations of cluster radio halos have given no sign of deviations from the steep power-law spectra. The only indication of a high-frequency cutoff is the suggestion by Schlickeiser, Sievers, & Thiemann (1987) that the Coma spectrum steepens exponentially above 0.15 GHz. They conclude that the steepening is best explained by in situ reacceleration of electrons in the IC space, but this interpretation is implicitly based on the assumption of steady state that they used. If, alternatively, Coma C is a fading relic, then the cutoff is naturally explained by radiative losses. Adopting the KP model, and scaling the expression for the cutoff frequency ν_c to the Coma parameters (radius $R = 500$ kpc, equipartition field $B = 1.5\ \mu$G, cutoff frequency $\nu_c = 0.15$ GHz), we obtain the following equation for x:

$$\frac{\kappa^{3/2}(x)\sigma^{1/2}(x)}{x^2} = 1.1 \times 10^{-3} N_{-2}^{-\frac{1}{2}} \left(\frac{\nu_c}{0.15\ \mathrm{GHz}}\right)^{-1} \left(\frac{B}{1.5\ \mu\mathrm{G}}\right)^{2} \left(\frac{R}{500\ \mathrm{kpc}}\right)^{-2}, \quad (25)$$

which is satisfied for $x \approx 20$ (with these values of the parameters). Thus, in this simple model, a total time $t \approx 1.1 \times 10^7$ yr elapsed since the beginning of the relic stage. In a homogeneous field one would not expect any emission at 150 MHz in the JP model, but in a random field the two models are practically indistinguishable.

Could the rate of ejection of energetic electrons have decreased throughout the full extent of the source after it had expanded to its present size? The spectrum breaks at 150 MHz after only $\sim 2.6 \times 10^8$ yr, and we must assume that the decrease in activity took place over a still shorter period of time (eq. [17] corresponds to an instantaneous cutoff of energy supply). Such short timescales are hardly plausible in a source whose size is ~ 1 Mpc. For the same reason it is difficult to explain diffuse cluster sources as merged remnants of many radio sources: radio galaxies are not that common, and one cannot simply assume that in all such galaxies activity weakened recently (and simultaneously).

If we assume that reduction of activity had spread over a long period of time, we should see a cutoff flatter than that expressed in equation (17). This may actually be the case; for instance, Schlickeiser et al. (1987) fitted the Coma C data to $\nu^{-1/2} \exp[-(\nu/0.15\ \mathrm{GHz})^{1/2}]$ instead of our ($p \approx 1.5$ follows from the power-law part of the spectrum) $\nu^{-1/2} \exp[-(\nu/\nu_c)]$. Yet another possibility is that the radio lobe expanded but the source of electrons remained compact, and its activity decreased about a few times 10^8 yr ago. However, in such a model electron diffusion must be taken into account; this results in a steep high-frequency cutoff (Tribble 1993).

The above considerations lead us to the conclusion that the only viable relic-type origin of Coma C, or Coma-like radio sources, is that with a progenitor (typical radius $R_0 \approx 25$ kpc and magnetic field $B_0 \approx 6 \times 10^{-4}$ G) which has been expanding for only a few times 10^7 yr. We must emphasize again that even this scenario is problematic: ones has to explain how the IC gas could be heated during this very recent epoch. It also should be kept in mind that in the future cluster sources may be found to be more common, if indeed the small number of currently known ones is due to the observational difficulty in separating the extended, low surface brightness emission from the many discrete radio sources found in clusters. If so, the short lifetimes, and the rather extreme values of the parameters of the progenitors, will perhaps be in conflict with a relic origin of IC radio sources. We think that although the relic hypothesis cannot be ruled out definitely at present, it is more likely that cluster radio sources are currently active, and that the electron energy distribution is (nearly) at a steady state, as a result of a continued replenishment of electrons originating either from a single powerful, central source or from most (if not all) of the cluster galaxies.

Finally, note that in principle the high-frequency cutoffs should be seen in the spectra of essentially all relics. The cutoff reaches sufficiently low frequencies (~ 1 GHz) at $x \gtrsim 5$ for a "typical" (i.e., $B_{-4} = R_{30} = N_{-2} = 1$) relic. Spectral data on relics (Harris et al. 1993; Goss et al. 1987; Cordey 1987) are insufficient to draw definite conclusions. The only exception is relic 1253+275, where no cutoff was detected up to at least 2.7 GHz (Giovannini et al. 1991). Taking into account the fact that the equipartition magnetic field in 1253+275 is around 1 μG (see below), the lack of a cutoff may be hard to reconcile with the identification of the source as a relic, unless in situ reacceleration is invoked in the peripheral region of the Coma cluster.

5. COMPTON X-RAY EMISSION FROM AGING RELICS

Detection of Compton X-ray emission from relics, as well as from clusters of galaxies, will be important for increased understanding of the astrophysics of these systems. The Compton flux is a direct measure of the energy density in relativistic electrons, and—combined with the synchrotron flux—of the volume-averaged magnetic field. Compton emission from clusters of galaxies has been searched for (see Rephaeli, Gruber, & Rothschild 1987; Bazzano et al. 1990; Rephaeli et al. 1994), but so far only upper limits have been obtained. Low-energy (below 20 keV) emission from clusters is dominated by thermal bremsstrahlung, and the existing detectors are not sensitive enough to observe the (much weaker) high-energy Compton emission. The detection of relics which are not in clusters might be more feasible, since the lack of thermal emission from the ambient medium makes a lower energy search (e.g., with *ROSAT*) possible.

The expected Compton flux depends crucially on the magnetic field in the source. One can get an estimate of the field from the synchrotron emission, assuming that the field is in energy equipartition with the relativistic particles. One can then use the estimated field to predict this flux. It should be stressed, however, that the equipartition assumption might be unrealistic, so predicted flux might be quite uncertain (see Goldshmidt & Rephaeli 1993 for discussion of other pertinent issues).

The predicted X-ray flux also depends on whether the source is in steady state or expanding and "aging," and whether the pitch angle distribution of the electrons is isotropic. As mentioned, the JP and KP models yield practically indistinguishable synchrotron spectra in a random magnetic field, but the Compton emission will be very different: at energies $\epsilon \gg \epsilon_1$ (ϵ_1 lies well below the region of interest to us; see eq. [31]) the JP model yields an exponentially low flux, while in the KP model the spectrum is a power law. Therefore, lack of X-ray emission at a sufficiently low level might be an indication that the source is "aging," the magnetic field is random, and the electrons are isotropic.

5.1. *Compton Emission of Aging and Steady State Sources*

From radio measurements alone it cannot be determined whether a radio source is in steady or expansionary state, unless a high-frequency cutoff is apparent. In contrast, while in the more conventional steady state case the Compton X-ray flux has the same power-law index as that in the radio, in an "aging" source the X-ray spectrum is flatter than in the radio.

One can calculate the magnetic field that corresponds to the minimum of the total energy in the relativistic particles and the field. The standard steady state calculation is described by (e.g.) Pacholczyk (1970). Similarly, in the case of an aging source with a steep power-law spectrum (see eq. [15]), we have

$$B_a = \left[\frac{4.5(1+K)\tilde{c}_{12}L}{\phi R^3}\right]^{2/7}, \tag{26}$$

where L is the radio luminosity of the source in the frequency band $[\nu_l, \nu_h]$, the energy in the heavy particles is assumed to be K times the energy of electrons, ϕ is the volume filling factor of the magnetic field, and $\tilde{c}_{12}$ is given by

$$\tilde{c}_{12} = \frac{1}{9\pi}\frac{\nu_1^{-(n+1)/2}}{n-1}\left[c_1^{1/2}c_3\,c_{10}\left(\frac{3n-1}{2}\right)c_{11}\left(\frac{3n-1}{2}\right)\right]^{-1}\frac{\nu_l^{3(1-n)/4}-\nu_h^{3(1-n)/4}}{\nu_l^{1-n}-\nu_h^{1-n}}. \tag{27}$$

To avoid further complications (eq. [27] fails when $n = 1$), we restrict ourselves to steep-spectrum sources only, $n > 1$. B_a differs from the steady state field value B_s by a factor (in the limit $\nu_h \gg \nu_l$)

$$\frac{B_a}{B_s} = \left\{\frac{2}{9}(2n-1)a(2n+1)\left[c_{10}\left(\frac{3n-1}{2}\right)c_{11}\left(\frac{3n-1}{2}\right)\right]^{-1}\left(\frac{\nu_l}{\nu_1}\right)^{(n+1)/4}\right\}^{2/7}. \tag{28}$$

[The function $a(p)$ is tabulated in Blumenthal & Gould 1970.] As an example, when $n = 1.33$, equation (28) yields $(B_a/B_s) \approx 0.16(\nu_l/\nu_1)^{0.17}$.

Assuming that the magnetic field is indeed given by equation (26), one can predict the Compton flux $f_C^{(a)}$ at energy ϵ by a known radio flux F_S at frequency ν and by radio spectral index n. However, since one often has a ready recipe for calculating the magnetic field B_s and the corresponding Compton X-ray $f_C^{(s)}$ in the steady state case, the following expressions may prove useful:

$$B_a = \left(\frac{B_s}{1\ \mu\mathrm{G}}\right)^{7/(6-n)}\left\{\frac{2}{9}(2n-1)a(2n+1)\left[c_{10}\left(\frac{3n-1}{2}\right)c_{11}\left(\frac{3n-1}{2}\right)\right]^{-1}\left[\left(\frac{\nu_l}{\nu_c}\right)\psi(x)\right]^{(n+1)/4}\right\}^{2/(6-n)}\mu\mathrm{G}, \tag{29}$$

$$\frac{f_C^{(a)}}{f_C^{(s)}} = 4.1\times10^{-3}(1.06)^{(n+3)/4}a(2n+1)\left[(n-1)c_{10}\left(\frac{3n-1}{2}\right)c_{11}\left(\frac{3n-1}{2}\right)\right]^{-1}\left(\frac{B_s}{1\ \mu\mathrm{G}}\right)^{n+1}\left[\frac{\psi(x)}{\nu_c}\left(\frac{1\ \mu\mathrm{G}}{B_a}\right)\frac{\epsilon}{kT}\right]^{(n+1)/4}. \tag{30}$$

To obtain these relations, we used the definition $\nu_1 = c_1 B E_1^2$, and the expressions for ν_1 and ν_c given in the end of § 3.2, and defined

$$\psi(x) = \left[\frac{\sigma(x)}{\kappa(x)}\right]^{-3/2}x^4. \tag{31}$$

Note that one must have estimates of ν_c and x to use the above results. Nevertheless, even when no cutoff is observed, the equations lead to a lower limit on B_a and to an upper limit on $f_C^{(a)}$. If the radio spectrum exhibits no deviations from a power law up to some frequency ν_h, then this frequency can serve as a lower limit to ν_c. With an upper limit on x, say $x = 30$ (eq. [4]), one can then use equations (29) and (30) to obtain a lower limit on B_a, and an upper limit on $f_C^{(a)}$ [using the fact that $\psi(x)$ is an increasing function of x].

5.2. *Application to Relics and Coma C*

Let us apply the above relations to some of the observed relic sources. The radio spectrum of Relic 0917+75 (apparently associated with the Rood No. 27 group of galaxy clusters; Harris et al. 1993; Dewdney et al. 1991) is very uncertain, and cannot be fitted with a simple function. Of more interest are Relic 0924+30 (associated with the galaxy IC 2476; Cordey 1987 and references therein) and Relic 1253+275 (adjacent to Coma C; Giovannini et al. 1991). Both have spectra that can be well fitted with power laws.

For Relic 0924+30 we get a good power-law fit (based on the data from Cordey 1987, Feretti et al. 1984, and Ekers et al. 1975, 1981):

$$F_S = (1.86 \pm 0.37)\times10^{-14}\nu^{-1.05\pm0.05}\ \mathrm{ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}}. \tag{32}$$

The equipartition magnetic field B_s is about 1.1 μG (we assume $K = 100$ and $\phi = 1$), so the predicted Compton flux in the steady state model is

$$f_C^{(s)} = 4.73\times10^{-5}\left(\frac{\epsilon}{1\ \mathrm{keV}}\right)^{-2.05}\left(\frac{B_s}{1.1\ \mu\mathrm{G}}\right)^{-2.05}\ \mathrm{photons\ cm^{-2}\ s^{-1}\ keV^{-1}}. \tag{33}$$

As mentioned, we are interested primarily in Compton flux around 1 keV, because sensitive detectors (e.g., *ROSAT*) are available in the energy range, and presumably there is no thermal emission from the source. For $z = 0.0266$ and $H_0 = 50$ km s^{-1} Mpc^{-1} we obtain a total luminosity between 0.5 and 2.5 keV of 3.7×10^{41} ergs s^{-1}. Such a source would not be detectable in the *ROSAT* sky survey database. Detection may be possible by a long pointing observation.

If, on the other hand, the source is expanding, then taking 1.4 GHz as the highest frequency at which the radio flux is measured, and $x = 30$ as an upper limit, we obtain

$$B_a > 0.13 \left(\frac{\nu_c}{1.415\ \mathrm{GHz}}\right)^{-0.2} \left[\frac{\psi(x)}{\psi(30)}\right]^{0.2} \mu\mathrm{G} \tag{34}$$

from equation (29), and

$$f_C^{(a)} < 1.4 \times 10^{-7} \left(\frac{\epsilon}{1\ \mathrm{keV}}\right)^{-1.55} \left(\frac{B_a}{0.13\ \mu\mathrm{G}}\right)^{-0.5} \left(\frac{\nu_c}{1.415\ \mathrm{GHz}}\right)^{-0.5} \times \left[\frac{\psi(x)}{\psi(30)}\right]^{0.5} \mathrm{photons\ cm^{-2}\ s^{-1}\ keV^{-1}} \tag{35}$$

from equation (30). Thus, the steady state flux (in eq. [33]) is significantly higher than the flux from an expanding relic.

The other relic source, 1253+275, was studied in detail by Giovannini et al. (1991). The best fit to their data is

$$F_S(\mathrm{relic}) = (1.55 \pm 0.56) \times 10^{-13} \nu^{-1.18 \pm 0.06}\ \mathrm{ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}}\ . \tag{36}$$

In this case we are primarily interested in Compton flux at energies above 50 keV, in view of the OSSE observations of Coma C (Rephaeli et al. 1994; the field of view of OSSE is large, so 1253+275 will contribute to the total flux). We calculate the equipartition field $B_s \sim 1\ \mu$G, and so

$$f_C^{(s)}(\mathrm{relic}) = 2.3 \times 10^{-8} \left(\frac{\epsilon}{40\ \mathrm{keV}}\right)^{-2.18} \left(\frac{B_{\mathrm{relic}}}{1\ \mu\mathrm{G}}\right)^{-2.18} \mathrm{photons\ cm^{-2}\ s^{-1}\ keV^{-1}}\ . \tag{37}$$

Compare this with the Compton flux predicted from Coma C. Its radio flux is

$$F_S(\mathrm{Coma}) = (8.3 \pm 1.5) \times 10^{-12} \nu^{-1.34 \pm 0.06}\ \mathrm{ergs\ cm^{-2}\ s^{-1}\ Hz^{-1}} \tag{38}$$

(Kim et al. 1990), and with an equipartition field $B_s \sim 1\ \mu$G we calculate

$$f_C^{(s)}(\mathrm{Coma}) = 6.5 \times 10^{-9} \left(\frac{\epsilon}{40\ \mathrm{keV}}\right)^{-2.34} \left(\frac{B_{\mathrm{halo}}}{1\ \mu G}\right)^{-2.34} \mathrm{photons\ cm^{-2}\ s^{-1}\ keV^{-1}}\ . \tag{39}$$

The latter flux may be a lower limit: this is the flux from the magnetized region; we expect X-ray emission from a much larger volume. For instance, if the electrons in Coma originate in a small central source and diffuse freely along magnetic field lines tangled at 20 kpc scale (as described by Goldshmidt & Rephaeli 1993), then the X-ray flux from a 6 Mpc size region is larger than the above value by a factor of $\sim$10.2. However, 1253+275 still contributes a significant fraction of the total flux, and in general one should carefully account for the emission from the relic when interpreting data from OSSE (and other detectors with large fields of view). Note also the strong dependence of the predicted X-ray fluxes on the values of the magnetic field, a dependence which constitutes a substantial uncertainty in the predicted fluxes.

We also estimated the soft X-ray from the source under the assumption that the emission would not be affected by thermal bremsstrahlung at this distance ($70' \approx 3$ Mpc) from the Coma center. Judging by the level of the background as determined in the *ROSAT* observations of Briel, Henry, & Böringer (1992), the emission is too low to be detectable by this experiment.

Finally, consider whether X-ray emission from 1253+275 could account for the emission from the Coma region reported by Bazzano et al. (1990). The flux, corrected for the residual thermal component, is (Rephaeli & Goldshmidt 1992)

$$f_B = (1.3 \pm 0.2) \times 10^{-4} \left(\frac{\epsilon}{40\ \mathrm{keV}}\right)^{-1.6 \pm 0.35} \mathrm{photons\ cm^{-2}\ s^{-1}\ keV^{-1}}\ . \tag{40}$$

This level of emission cannot be interpreted as diffuse emission from Coma, and its origin is still unknown (Rephaeli & Goldshmidt 1992). The spectral index in the latter fit, which has a large uncertainty, is consistent—within 1.7 σ—with that of equation (36). Therefore, a consideration of the implications of the possibility that this flux (f_B) is produced by the electrons in the relic is appropriate. Assuming that the X-ray flux has the same power-law index (1.18) as the radio flux, and keeping the same total 18–130 keV luminosity, we obtain a very low value for the magnetic field in 1253+275, $B \approx 6 \times 10^{-3}\ \mu$G, and a corresponding high energy density in electrons, $\rho_e \approx 6 \times 10^{-12}$ ergs cm^{-3} (the latter value is higher than the energy density of cosmic-ray *protons* in the Galaxy). Thus, this interpretation of the emission detected by Bazzano et al. leads to untenable implications.

How would the estimates in equations (37) and (39) change if we assumed that both 1253+275 and Coma C were expanding relics? The spectrum of 1253+275 is measured up to 2.7 GHz. From equation (29) we obtain

$$B_a > 0.13 \left(\frac{\nu_c}{2.7\ \mathrm{GHz}}\right)^{-0.23} \left[\frac{\psi(x)}{\psi(30)}\right]^{0.23} \mu\mathrm{G}\ , \tag{41}$$

and from equation (30),

$$f_C^{(a)}(\mathrm{relic}) < 1.4 \times 10^{-10} \left(\frac{\epsilon}{50\ \mathrm{keV}}\right)^{-1.64} \left(\frac{B_a}{0.13\ \mu\mathrm{G}}\right)^{-0.54} \left(\frac{\nu_c}{2.7\ \mathrm{GHz}}\right)^{-0.54} \left[\frac{\psi(x)}{\psi(30)}\right]^{0.54} \mathrm{photons\ cm^{-2}\ s^{-1}\ keV^{-1}}\ . \tag{42}$$

In the case of Coma C, the most meaningful estimate would be associated with the suggestion by Schlickeiser et al. (1987) of a cutoff above 150 MHz, correspond to $x = 20$ (see the discussion in the previous paragraph). Equations (29) and (30) then yield

$$B_a = 0.5\left(\frac{\nu_c}{150\ \mathrm{MHz}}\right)^{-0.25}\left[\frac{\psi(x)}{\psi(20)}\right]^{0.25}\ \mu\mathrm{G}\ , \tag{43}$$

and

$$f_C^{(a)}(\mathrm{Coma\ C}) = 5.55 \times 10^{-11}\left(\frac{\epsilon}{50\ \mathrm{keV}}\right)^{-1.75}\left(\frac{B_a}{0.5\ \mu\mathrm{G}}\right)^{-0.59}\left(\frac{\nu_c}{150\ \mathrm{MHz}}\right)^{-0.59} \times \left[\frac{\psi(x)}{\psi(20)}\right]^{0.59}\ \mathrm{photons\ cm^{-2}\ s^{-1}\ keV^{-1}}\ . \tag{44}$$

As in the case of 0924+30, the "aging" model yields much lower X-ray fluxes than the steady state one, despite a flatter predicted X-ray spectrum. The relative contributions of 1253+275 and Coma C remain qualitatively the same. It should be noted that detection of X-ray flux from Coma at a level not too much lower than the present OSSE upper limit ($\sim 6 \times 10^{-6}$ photons $\mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}$ at 50 keV; Rephaeli et al. 1994) may be construed as evidence that the source is in steady state.

6. CONCLUSION

We have carried out a detailed study of spectral evolution of a fading radio remnant. Our results are presented in a general form, independent of the particular details of the expansion of the remnant into the ambient IG medium. Synchrotron, Compton, and expansion losses, and the change of the magnetic field during the expansion, are all taken into account in a consistent way. Both the synchrotron and Compton spectra of such a remnant develop breaks at low frequency (energy), and exponential cutoffs at high frequencies (energies), due to radiative losses.

These spectral features, along with size, morphology, and physical parameters, suggest that such relic sources may be close relatives of extended cluster sources (such as Coma C). However, the large value of the gas-to-magnetic pressure ratio in clusters implies that the expansion should have taken place at a rather early stage of cluster evolution. If that were the case, these sources would not be detectable at present. Furthermore, we have shown that since no cutoffs have been clearly observed in cluster radio spectra, it is doubtful whether there is no ongoing ejection of energetic particles into the IC space. Favored models are those in which the electrons (emanating from a single radio source, or from the cluster galaxies) maintain a steady state energy distribution.

We have estimated the predicted X-ray fluxes from two interesting relics. Nonthermal X-ray emission from relic 0924+30 in the *ROSAT* band will not be dominated by thermal emission. Detection of Compton flux from this or a similar source would yield valuable information on some of its physical properties (magnetic field, relativistic electron energy density). Compton emission from 1253+275 in the Coma neighborhood has to be accounted for in the interpretation of measurements of Coma, such as that by OSSE.

Our estimates of Compton X-ray fluxes for Coma C and the two relics lead to much smaller values in the "aging" model as compared to the steady state one. This means that even when the high-frequency cutoff in the radio spectrum is not observed, X-ray observations may in principle enable testing of the predictions of the two models. However, the present-day detectors seem to be at best marginally sensitive to the most optimistic estimates of predicted emission levels.

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