THE BROADBAND SPECTRUM OF GALAXY CLUSTERS

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ABSTRACT

We examine whether nonthermal protons energized during a cluster merger are simultaneously responsible for the Coma cluster’s diffuse radio flux (via secondary decay) and the departure of its intracluster medium (ICM) from a thermal profile via Coulomb collisions between the quasi-thermal electrons and the hadrons. Rather than approximating the influence of nonthermal proton/thermal electron collisions as extremely rare events which cause an injection of nonthermal, power-law electrons (the knock-on approximation), we self-consistently solve (to our knowledge, for the first time) the covariant kinetic equations for the two populations. The electron population resulting from these collisions is out of equilibrium, yet not a power law, and importantly displays a higher bremsstrahlung radiative efficiency than a pure power law. Observations with GLAST will test this model directly.

Subject headings: acceleration of particles — galaxies: clusters: individual (Coma) — radiation mechanisms: nonthermal — relativity — X-rays: galaxies

1. INTRODUCTION

Galaxy clusters, aggregates of more than 50 individual galaxies interspersed with a tenuous plasma known as the intracluster medium (ICM), are the largest gravitationally bound objects in the universe. Mergers of such clusters are the most energetic astrophysical events since the big bang: a merger of two $10^{15} M_\odot$ clusters releases some $10^{63} - 10^{64}$ ergs of gravitational energy.

Aside from providing heat (see, e.g., Brunetti et al. 2001; Ohno et al. 2002; Fusco-Femiano et al. 1999; Rephaeli et al. 1999) observed as bremsstrahlung emission in the ICM (where the X-ray luminosity is typically served as bremsstrahlung emission in the ICM (where the X-ray luminosity is typically $L_X \sim 10^{45}$ erg s$^{-1}$, temperatures are in the range $\sim 2-10$ keV, and the central density is $\sim 10^{-3}$ cm$^{-3}$), such merger events also create supersonic shocks capable of accelerating nonthermal particles to energies greater than 1 TeV (Loeb & Waxman 2000). Examples of such shocks known to be ongoing in cluster mergers include the galaxy group NGC 4839, falling toward the center of the Coma cluster, as observed by XMM-Newton (Neumann et al. 2001). NGC 4839 achieves a velocity of $\sim 1400$ km s$^{-1}$, and since the sound speed corresponding to Coma’s gas temperature of $\sim 8$ keV is $\sim 1000$ km s$^{-1}$, the subcluster’s supersonic motion is expected to produce shocks, which Neumann et al. (2001) claim to observe directly in the imaging of this cluster. Chandra observations of the “bullet” cluster 1E 0657-558 (Markevitch et al. 2002, 2004) show a prominent bow shock from a lower mass subcluster ($T \approx 6$ keV) as it exits the core of the main cluster ($T \approx 14$ keV) at a velocity of 4500 km s$^{-1}$. Within such shocks, some small fraction—typically $\sim 5\%$ (see, e.g., Berrington & Dermer 2003)—of the gravitational energy provided by the merger is believed to be converted into nonthermal particles through a first-order Fermi (Drury 1985) process, although neither of the above cases provides direct evidence for such acceleration.

Further evidence for a population of accelerated, nonthermal particles coexisting with the thermal background ICM comes from diffuse radio emission extending over the entire $\sim 1$ Mpc extent of certain rare clusters. Radio luminosities (polarized in at least one case), $L_r \sim 10^{40} - 10^{43}$ ergs s$^{-1}$, have been measured from emitting regions extending over a Mpc in 30 or so galaxy clusters (see, e.g., Kim et al. 1990; Giovannini et al. 1993; Giovannini & Feretti 2000; Kempner & Sarazin 2001). This emission—characterized as “halo” if it is radially concentrated at the cluster center and “relic” if instead it is located on the cluster’s outskirts—indicates synchrotron emission of relativistic electrons in a magnetized intracluster medium. Radio halos (such as the Coma cluster, which takes our focus here) further require a mechanism for constantly replacing energy lost by nonthermal electrons, since their radiative lifetimes (around $10^8$ yr) are too short to allow electrons to diffuse across the 100 kpc radio emitting region. The radial shape of halo emission, in particular, requires that nonthermal electrons be constantly created throughout the cluster.

One natural explanation (Dennison 1980) is that cosmic-ray protons, known to be confined within the cluster once produced—perhaps diffused throughout the cluster following a merger, although a central active galactic nuclei (AGN; Blasi & Cefafrancesco 1999) could also create sufficient nonthermal hadron energy—constantly collide with hydrogen and lose sufficient energy to create pions, which subsequently decay into the synchrotron-emitting electrons. However, due in part to difficulties reconciling this secondary model with all multifrequency observations (Blasi & Cefafrancesco 1999), it is often assumed electrons are constantly reaccelerated in situ by a second-order Fermi mechanism (see, e.g., Blasi 2000).

In the Coma cluster and a dozen others (Dolag & Ensslin 2000), the diffuse radio emission exhibits a spectral break around 1 GHz, with a steeper index at higher energy. Entire models have been based on this break, interpreted as the signature of electron escape (Rephaeli 1979), of a reacceleration of already relativistic electrons—possibly energized by a cluster merger event (Schlickeiser et al. 1987; Brunetti et al. 2004)—or of energy-dependent radiative losses acting to impose a maximum electron energy during shock acceleration itself (Berrington & Dermer 2003; Webb et al. 1984; Dolag & Ensslin 2000). Notably, the secondary model we are proposing here does not reproduce this spectral steepening. Instead, it aims to reconcile past X-ray and future $\gamma$-ray observations using the simplest possible assumptions for the spectrum of accelerated particles, namely a pure power law. The model posits that Coulomb collisions between the cluster’s high-energy proton population and its thermal electrons are the root of nonthermal excesses in the extreme-ultraviolet (EUV) and X-ray regimes. This is the novel component of this

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picture, replacing the knock-on approximation with a full solution to the kinetics involved (see §2).

Clusters produce an X-ray luminosity \( L_X \sim 10^{45} \text{ ergs s}^{-1} \), generally interpreted as being due to thermal bremsstrahlung by a tenuous thermal plasma characterized by a temperature in the range \( \sim 2-10 \text{ keV} \) and a central density \( \sim 10^{-3} \text{ cm}^{-3} \). These thermal X-ray emitting leptons coexist with the nonthermal radio-emitting leptons. Several clusters also display a slight excess above the thermal spectrum starting at \( \sim 20-25 \text{ keV} \) and extending out to energies greater than \( \sim 45 \text{ keV} \). Although still somewhat controversial, this nonthermal component has thus far been reported for the Coma cluster (Fuso-Femiano et al. 1999; Rephaeli et al. 1999), Abell 2256 (Fuso-Femiano et al. 2000), and most recently for Abell 754 (based on long BeppoSAX observations; Fuso-Femiano et al. 2003). Hard X-ray detections have been reported in several other Abell clusters (2199, 2319, and 3667) in the redshift range \( 0.023 < z < 0.056 \), although apparently with weaker signals. Most of these excesses above the thermal emission can be fitted with a photon power-law spectrum and index \( \sim 2 \). A recent example of this fitting procedure, applied to the Rossi X-Ray Timing Explorer (RXTE) source RX J0658, can be found in Petrosian (2004).

An interpretation of the X-ray excess (HXR) as inverse Compton scattering (ICS) of synchrotron-emitting electrons breaks a degeneracy in the possible values of ICM magnetic field and electron energy (see, e.g., Rephaeli 1979). If the same electrons are responsible for both the radio synchrotron and nonthermal X-ray emission, then the implied magnetic field \( B \) must be an order of magnitude smaller than that observed. In the Coma cluster, for example, Faraday rotation measurements suggest that \( B \sim 6 \mu \text{G} \) (Feretti et al. 1995), in sharp contrast with the value derived from BeppoSAX observations (within the context of the inverse Compton scattering scenario), which instead require \( B \sim 0.16 \mu \text{G} \) (Fuso-Femiano et al. 1999).

It can also be supposed that, in addition to the bremsstrahlung-emitting thermal ICM and synchrotron-emitting nonthermal electrons, a third nonthermal population of electrons exists which emits the X-ray excess (HXR) as bremsstrahlung. Were such a population thermal, it would require a high temperature (\( >50 \text{ keV} \)), impossible to maintain against Coulomb re-equilibration if the species were not physically separated. Previously, Blasi (2000) suggested that hard X-ray emission in galaxy clusters may be due to bremsstrahlung radiation from a population of nonthermal electrons energized continuously out of the thermal pool via stochastic acceleration (see also Dogiel 2000; Sarazin & Kempner 2000; see also Liu et al. [2004] for a more recent treatment of this process). But the re-equilibration timescale of \( \sim 1 \text{ Myr} \), in the absence of an efficient energy-loss mechanism, means that all the energy given to the nonthermal component has been reprocessed into the thermal pool well before \( \sim 0.5 \text{ Gyr} \), heating the ICM above its observed temperature in less than \( 10^8 \text{ yr} \) (Petrosian 2001; Wolfe & Melia 2006b).

It was, however, suggested by Liang et al. (2002) and Dogiel et al. (2007) that a quasi-relativistic third population might overcome this difficulty via a higher radiative efficiency (and therefore a longer overheating time). Our model shares this characteristic, but rather than requiring a second-order Fermi acceleration to produce the quasi-relativistic particles, we assume they are produced via collisions with nonthermal protons. This appears to be quite natural, since it has long been believed that electrons accelerated via collisions with cosmic rays, known as knock-on electrons, are more abundant than those produced by secondary decay in the \( \gamma_e < 100 \) region (Schlickeiser 1999; Baring 1991). Our approach is simply to solve the kinetic equation of electrons, including both the standard terms (secondary injection, radiative losses, re-equilibration, etc.) and collisions with nonthermal protons. These protons are then simultaneously responsible for both the radio-emitting electrons and the nonthermal component of hard X-rays.

An additional motivation for this model is a somewhat controversial excess over the expected thermal bremsstrahlung that has been reported in the EUV: in Coma an excess was reported at \( 1.4 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1} \) (Bowyer et al. 2004; Sarazin & Lieu 1998). Observations of an EUV excess have also been claimed in the Virgo and Abell clusters 1795, 2199, and 4059 (Durret et al. 2002). The standard interpretation for these observations is ICS of the cosmic microwave background by relativistic electrons. The Extreme Ultraviolet Explorer (EUVE) measurement is curious because an ICS interpretation probes precisely the \( 10 < \gamma_e < 100 \) portion of the electron distribution. Here, we show that secondary electrons alone cannot account for the EUVE, because the source function for electrons injected via proton-hydrogen scattering departs from a pure power law at the relevant energies. We propose instead that the EUVE demonstrates the presence of electrons accelerated to high energies via proton-electron collisions.

By far the most significant motivating factor, however, is the possibility of observing \( \gamma \)-rays within a galaxy cluster. While no such observation has been confirmed (see, e.g., Reimer 2004), simple arguments (see below) show that a positive \( \gamma \)-ray flux from secondary decays in the Coma and other clusters should certainly lie within the sensitivity of the Gamma-Ray Large Area Space Telescope (GLAST) satellite.

In nine years of observation, the EGRET telescope on board Compton Gamma Ray Observatory gave only upper limits for the \( \gamma \)-ray flux of the most X-ray bright galaxy clusters, and it is here that our model receives its strongest test. In the case of the Coma cluster (\(<3.8 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \); Reimer 2004), the \( \gamma \)-ray limit excludes the secondary model from consideration if the magnetic field within the cluster is \( B < 1 \mu \text{G} \) (Blasi & Colafrancesco 1999)—i.e., if the inverse Compton interpretation of the X-ray excess, and not Faraday rotation, correctly gives the magnetic field value—because a small magnetic field requires a detectably significant population of nonthermal hadrons.

Therefore, the significant contribution of the scenario we present here is the reconciliation of the secondary model with high magnetic field values and the X-ray excess, in the simplest possible manner. In this picture, cosmic-ray protons diffuse evenly throughout the cluster. They collide with hydrogen in the intracluster medium, producing a decay cascade whose products include electrons and \( \gamma \)-rays, each peaked at 70 MeV. These electrons, in magnetic fields \( >1 \mu \text{G} \), develop diffuse radio emission. The cosmic-ray protons also collide with background thermal electrons and knock the tail of these electrons into a quasi-thermal third population. It is this third population, we believe, which is responsible for the EUV and hard X-ray excesses.

But this (perhaps still overly simplified) model notably fails to predict the spectral steepening at 1 GHz in Coma, as well as the radial dependence of the radio spectral index. The competing reacceleration model, in which already relativistic relic electrons are re-energized by a second-order stochastic acceleration process stirred by cluster mergers, already handles these details well. However, a non-ICS interpretation of the X-ray excess will become necessary should the GLAST satellite observatory, the H.E.S.S. telescope, or others confirm a positive \( \gamma \)-ray flux in the Coma cluster. The model presented here is a simple alternative which would be motivated mainly by such a positive detection.
2. COSMIC-RAY KINETICS

While our model proposes cosmic ray/electron collisions as a mechanism for producing the X-ray excess, it is important to stress a distinction between our approach and the commonly used knock-on approximation (Abraham et al. 1966). That model was first proposed to describe an observed population of low-energy cosmic-ray electrons which exceeded the number expected from pion decay at the 70 MeV threshold. To make up for the discrepancy, cosmic ray/electron Coulomb collisions were proposed as a dominant mechanism for electron production in the 20 < \gamma_\mathrm{e} < 200 regime.

In the knock-on approximation, collisions are considered rare events which cause such radical change in the electron’s energy that electrons simply appear at the higher energy. Such injected electrons match the proton’s spectral index at a rate proportional to the Coulomb cross section for interaction (Baring 1991). Thus to account for the cosmic ray/electron kinetics, one would need to break kinetics in two, with large-angle collisions represented as an injection \( Q(u) \) and small-angle collisions as the standard Boltzmann equation. More recently, however, complete covariant kinetic theories have appeared (Lifshitz & Pitaevskii 1958; Nayakshin & Melia 1998; Wolfe & Melia 2006b). If one were to break these theories into two parts at the outset—for small and large angles—one would find that the large-angle collisions are overwhelmed to the point of irrelevance (Nayakshin & Melia 1998), bringing the basic assumption of the Abraham et al. (1966) approximation into question. And besides, if cosmic ray/electron collisions were in fact to provide a pure power-law injection, they would not be a candidate for producing Coma’s hard X-ray excess.

Particle collisions between protons and electrons cause the electrons to diffuse to higher energies, using a formalism very similar to the standard (Rosenbluth et al. 1957) theory. In that theory, the diffusion and advection of particles in velocity space are given by convolving the particle distribution with the kernels \(|v - \nu^*|\) and \(|v - \nu'|\). In the covariant generalization, these kernels must be corrected to (Landau 1936; Braams & Karney 1987; Wolfe & Melia 2006b)

\[
D_{\nu}(u) = \frac{q_e^2 q_h^2}{m_e^2} \Lambda \int Z(u, u') f(u) du, \tag{1}
\]

\[
F_{\nu_0}(u) = \frac{q_e^2 q_h^2}{m_e m_h} \left\{ 1 + \frac{m_e}{m_h} \Lambda \int \left[ \frac{\partial}{\partial u} Z(u, u') \right] f(u) du \right\}. \tag{2}
\]

Here and throughout \( u \equiv \gamma/\beta c \) is the momentum in units of the rest mass.

Collisions between the nonthermal background of intracluster electrons and nonthermal hadrons are then solved via a coupled Fokker-Planck equation (see Wolfe & Melia 2006b). It is not difficult to understand how collisions develop the nonthermal electron distribution, especially in contrast with the knock-on approximation which has, up to now, been used.

Baring (1991) holds that only large-angle collisions provide relativistic boosts to electrons, and this forms the basis of the knock-on approximations’ philosophy. The Fokker-Planck equation including knock-on injection is a kind of Frankenstein monster which handles \( e-p \) collisions once as a flux in the electron’s velocity space, and then again as a separate electron injection. But knock-on electrons are in fact proposed to describe relatively small jumps in energy, up to only 20 < \gamma_\mathrm{e} < 200, after which secondary production is expected to dominate. In writing the covariant Fokker-Planck equation, we have already made a small-angle assumption: consider instead equation (13) in Nayakshin & Melia (1998) for the energy exchange rate before a small-angle assumption is made. As is shown in this paper, if one were to break this integral into a large angle and a small angle, the large-angle component, which represents knock-on electrons, would be vastly dominated by energy exchanged in small-angle collisions. Proton-electron collisions do produce nonthermal electrons. But they should be handled within the normal kinetic context, by supposing that such collisions require the solution of a coupled Fokker-Planck equation.

Inspection of the diffusion coefficient (Nayakshin & Melia 1998) for a thermal distribution of electrons and a power-law population of protons reveals that proton collisions dominate over electron collisions when the electron’s momentum is \( \gamma_\mathrm{e} \sim m_e/c^2 \). This should be compared with the second-order Fermi diffusion coefficient used in previous studies (e.g., Blasi 2000). Collisional diffusion is less efficient, although of the same order, in the relevant energy range. Note that, while the power-law diffusion coefficient \( D_{\nu_0}(E) \sim E^n \) will inevitably lead to a power-law tail for the electrons, the diffusion coefficient for collisions always falls to a constant, yielding a distribution which must go to zero. That is, collisions with a power-law distribution cannot themselves yield another power law. Unlike under the knock-on approximation, electron collisions with power-law protons actually result in a nonthermal electron tail, steeper than the proton distribution, and featuring a hard cutoff at high energies. We call such electrons quasi-thermal. Distinguishing quasi-thermal electrons from the power-law distributions produced by turbulent diffusion or under the traditional knock-on approximation is essential, because their efficiency of bremsstrahlung emission is different (Liang et al. 2002; Dogiel et al. 2007).

3. EMISSION TYPES

Our actual calculation is time dependent and exact. However, we can gain a significant grasp of the model characteristics with a few simple analytic estimates. If we adopt the high-energy relation of Mannheim & Schlickeiser (1994) for the pion production rate of a power-law distribution of protons with index \( s \),

\[
q_{\pi^\pm}(E_{\pi}) = q_{\gamma^*}(E_{\pi}) \approx 13.1 c n_{\pi_0} n_{H_0} \sigma_{pp} \left[ \frac{E_{\pi}}{1 \text{ GeV}} \right]^{-4/3}(\gamma_{\pi} - 1/2), \tag{3}
\]

we can easily arrive at an approximate \( \gamma^* \)-ray source function,

\[
q_{\gamma^*}(E_{\gamma}) = 2 \int_{E_{\gamma}^{1/4}(4\pi c)}^{\infty} dE_{\pi} q_{\gamma^*}(E_{\pi}) (E_{\pi}^2 - m_e^2 c^4)^{-1/2}, \tag{4}
\]

which we may safely expect (Markoff et al. 1997; Fatuzzo & Melia 2003; Crocker et al. 2005) will also approximate the number of neutrinos injected per unit volume, per unit time (both in the high-energy limit). Meanwhile, the rate of electron injection is

\[
q_e = \frac{m_e}{70 m_e} q_{\pi^\pm} \left( \frac{E_{\pi}}{70 \text{ MeV}} \right) \approx \frac{13}{12} \sigma_{pp} c n_{\pi_0} n_{H_0} (r) \left( \frac{m_p}{24 m_e} \right)^{s_\nu - 1} (\gamma_{e}^* \beta_{e}^* \gamma_{\nu}^*)^{s_\nu} \text{ cm}^{-3} \text{ s}^{-1}
\]

\[
\equiv K_\nu \gamma_e^{-s_\nu}, \tag{5}
\]

where the electron spectral index \( s_\nu = (4/3)(s - 1/2) \) matches that of the pions. We find that these approximations are valid to...
within a factor 3 above the threshold energy for pion production at 70 MeV (Markoff et al. 1997).

Assuming the dominant loss mechanism is either inverse Compton scattering with a blackbody photon background \((T_{CMB} = 2.73 \text{ K})\), or radio synchrotron (Wolfe & Melia 2006a), radiative losses are given by \(dE/dt = a_i E_i^2\), with the constant \(a_i = (4/3)\sigma T \epsilon_{CMB} / m_e c^2\). The energy density \(\epsilon_{CMB}\) in the cosmic microwave background (CMB) dominates (by over a decade) over that \((\epsilon_\gamma)\) in the magnetic field. The equilibrium distribution of electrons due to injection against these losses is

\[
n(\gamma_e) = \frac{K_{\text{inj}}}{m_e c^2 a_i(s\epsilon_0 - 1)} \gamma_e^{-(s\epsilon_0 + 1)}.
\]

The ratio synchrotron emissivity (in units of energy per unit volume, per unit time, per unit frequency) associated with this distribution is then

\[
\frac{dE}{dV d\nu dt} \approx 1.15 \nu^2 \frac{K_{\text{inj}} \alpha \hbar \nu \gamma}{m_e c^2 a_i(s\epsilon_0 - 1)} \left(\frac{\nu_B}{\nu}\right)^{s\epsilon_0 / 2},
\]

where \(\nu_B\) is the gyrofrequency, and the corresponding Compton scattering emissivity off the CMB (in units of photon number per unit volume, per unit time, per unit energy) is

\[
\frac{dN_e}{dV d\epsilon d\theta} = 1.8 \frac{r_0^2}{\hbar^2 c^2} \frac{K_{\text{inj}}}{m_e c^2 a_i(s\epsilon_0 - 1)} (kT_{CMB})^{(s\epsilon_0 + 2)/2} \epsilon^{-s\epsilon_0 - 1}(s\epsilon_0 + 2),
\]

where \(r_0\) is the classical electron radius, and we have used the fact that the hard X-radiation is produced below the Klein-Nishina region to simplify the cross section. Note that, while the synchrotron emissivity varies roughly as the square of the magnetic field, inverse Compton scattering depends only on the relative normalization \(K_{\text{inj}}\) of electrons required for consistency with radio observations.

Finally, thermal bremsstrahlung emission in the relativistic region is approximated using a Gaunt factor (Rybicki & Lightman 1985) representing the multiplicative difference between quantum-nonrelativistic and QED (Haug 1997) bremsstrahlung cross sections. It can be reconstructed to better than \(-5\%\) accuracy as

\[
\tilde{g}_\nu(\phi) = A \log(\phi) + B + C\phi^D + E\phi^F
\]

where \(A\) through \(B\) are functions of \(\theta\) alone,

\[
A, B, E, \text{ and } F = a_i \theta^\nu + c_i \theta^\delta + e_i,
\]

\[
D = 1.95,
\]

\[
C = a_3 \theta^\nu + c_3 \theta^\delta \exp(-e_3 \theta),
\]

and where \(\phi = \nu / kT\) and \(\theta = kT / m_e c^2\). These coefficients are given in Table 1.

4. MODEL CHARACTERISTICS

Our guide for reasonable magnetic fields, particle densities, etc., is both a simultaneous fit of multifrequency observations and a maximum total energy budget being the power dissipated in a central merger event between two clusters of mass \(M\), which is

\[
L_p \sim 0.1 \frac{GM^2}{R_{\text{sh}} c} \sim 10^{44} \text{ ergs s}^{-1},
\]

where the shock radius \(R_{\text{sh}}\) is \(\sim 5\) Mpc, and the cluster’s age \(t_{\text{sh}} \sim 10^{10}\) yr.

Assuming an ICM gas mass \(M_{\text{gas}} \sim 10^{14} M_\odot\) and a total cluster mass \(M_{\text{cl}} \sim 10^{15} M_\odot\), over an active distance comparable with the Abell radius, the average ICM gas density is \(n_i \sim 3 \times 10^{-4} \text{ cm}^{-3}\). We adopt a magnetic field \(B = 0.8 \mu G\), which would underproduce inverse Compton scattered photons at the X-ray excess by roughly 2 orders of magnitude. We accept a recent estimate for the Coma’s distance of 102 Mpc; at a bremsstrahlung temperature \(T = 8.21 \text{ keV}\), the measured X-ray luminosity then implies an active volume \(\sim 1.5 \text{ Mpc}^3\). Finally, we take the spectral index \(\beta_p\) of the proton distribution \(n_p = n_{p0}(\gamma)/\gamma\) to have the value \(2.1\). The end result is a nonthermal hadron population consistent with a cosmic-ray luminosity \(L_p = 4.5 \times 10^{43} \text{ ergs s}^{-1}\), within the energy budget of a cluster merger.

5. PARTICLE DISTRIBUTION FUNCTION AND BROADBAND FLUX

We show the evolution of the quasi-thermal component of the electron distribution in Figure 1 (left), together with bounding thermal distributions to demonstrate its nonthermal character. The power-law tail is most pronounced after only \(10^7\) yr; however, the efficient energy loss via electron-proton collisions (bremsstrahlung) prevents rapid overheating and leads to a quasi-steady state distribution. Evolution of the nonthermal component is shown in Figure 1 (left); while the high-energy component assumes essentially the form of a pure power-law injection subject to synchrotron losses, the pion threshold region rapidly thermalizes.

Radio synchrotron emission (Fig. 2, left) comes from the purely power-law component of injected electrons. Clusters require at least some 100 Myr to reach their steady state, characterized by a power-law index one greater than the injection index. Nonthermal X-ray bremsstrahlung (Fig. 2, right) shows an excess consistent with that observed via BeppoSAX (Fusco-Femiano et al. 2003), although less consistent with the RXTE (Rephaeli
Gruber (2002) observations. As expected, ICS emission falls well below the required excess with any magnetic field $B$. The reported EUV excess (Bowyer et al. 2004; Sarazin & Lieu 1998) cannot be due to inverse Compton scattering of CMB photons by the nonthermal component of secondary electrons, because this emission comes from the threshold region, and where Coulomb losses dominate. Even supposing a magnetic field of $0.2 \mu$G, the inverse Compton flux at $2 \times 10^2$ eV falls several decades short of the excess power reported by Bowyer et al. (2004) (see Fig. 3).

The detection limits of EGRET and GLAST straddle the 70 MeV pion bump, so it is worthwhile improving on the rough sketch we have outlined above for the $\gamma$-ray emissivity by considering a more exact treatment. In Figure 4 we display the $\gamma$-ray flux consistent with both the diffuse radio and X-ray emission. For energies above $E_\gamma > 100$ MeV, the approximation (thick solid line) holds well. Note that the $\gamma$-ray luminosity produced by nonthermal electron-proton bremsstrahlung is always several decades below that produced via pion decay.

6. CONCLUSIONS

Previously (Liang et al. 2002; Dogiel 2006) it was shown that because the efficiency of bremsstrahlung emission for a quasithermal distribution is decades higher than for a pure power law
This type of distribution may account for the nonthermal X-ray excess. However, it was believed that proton collisions did not qualify, since under the knock-on approximation they produce electrons in a power law. Here, by solving the covariant kinetics self-consistently, we have shown that collisions do create a suitable quasi-thermal distribution. As further motivation that nonthermal proton/quasi-thermal electron collisions are in fact relevant in clusters, we have shown that electrons injected during proton collisions may not account for the EUV excess via inverse Compton scattering with the CMB, because the relevant injection occurs below the 70 MeV pion bump.

Describing the X-ray excess as due to a quasi-thermal electron population allows us to model the Coma cluster of galaxies using a value for the magnetic field in the intracluster medium which agrees with that given by Faraday rotation measurements. Luckily, our model has a near-term litmus test via the GLAST satellite:

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