(NASA-TM-86117) PHOTON-PHOTON ABSORPTION AND THE UNIQUENESS OF THE SPECTRA OF ACTIVE GALACTIC NUCLEI (NASA) 16 p HC A02/MF A01 CSCL 03B

N84-32338

Unclas G3/93 21330

NASA

Technical Memorandum 86117

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Demosthenes Kazanas

MAY 1984

National Aeronautics and Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

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Demosthenes Kazanas

NASA, Goddard Space Flight Center, Code 665

Greenbelt, MD 20771

and

Physics Department, University of Maryland,

College Park, MD 20742

ABSTRACT

The effects of the feedback of e^+-e^- pair reinjection in a plasma due to photon photon absorption of its own radiation is examined. Under the assumption of continuous electron injection with a power law spectrum $E^{-\Gamma}$ and Compton losses only , it is shown that for $\Gamma < 2$ the steady state electron distribution function has a unique form independent of the primary injection spectrum. This electron distribution function can, by synchrotron emission, reproduce the general characteristics of the observed radio to optical active galactic nuclei spectra. Inverse Compton scattering of the synchrotron photons by the same electron distribution can account for their X-ray spectra, and also implies gamma ray emission from these objects. This result is invoked to account for the similarity of these spectra, and it is consistent with observations of the diffuse gamma ray background.

1. Introduction

The X-ray observations of active galactic nuclei (hereafter AGNs) have demonstrated a remarkable similarity of their spectra: They are all very well fitted by power laws over almost two decades in energy with a rather unique photon index $\alpha \simeq 1.6$ (Rothschild et al. 1983), independent of the rest characteristics of the observed source i.e. its total luminosity and overall morpholgy. It is worth pointing out that similar statistical arguments have been made about the radio spectral indices of AGNs (de Bruyn and Wilson 1976) and the 3CR radio sources (Kellerman 1966). This similarity argues strongly for a common underlying radiation mechanism. The mechanisms suggested so far to account for the observed X-ray spectra of AGNs fall in two broad classes (thermal and non-thermal) depending on the character of the underlying electron distribution function responsible for the radiation. In the thermal category the X-rays are produced by inverse Compton scattering (hereafter IC) of soft photons off a thermal distribution of hot (kT ~ 100 keV) electrons (Katz 1976; Shapiro, Lightman and Eardley 1976). The resulting radiation has then a power law spectrum whose index depends only on the Comptonizatiom parameter $y = (kT/m_e c^2)\tau$ of the sources. The similarily of the spectra according to this mechanism is then due to the similarity of the y parameter of the sources. In the non-thermal category, the observed power law spectra have their origin in an underlying power law electron distribution. These electrons produce via synchrotron radiation radio frequency photons, which in turn by IC off the same power law electron distribution boost their energies to X and gamma ray energies (Jones, O'Dell and Stein 1974; Mushotzky 1978). The uniqueness of the spectra in this case is attributed to the uniqueness of the underlying electron power law distribution. Recently a third alternative has been proposed by Meszaros (1983), who considered thermal bremsstrahlung radiation from spherically symmetric accreting flows. He pointed out that the flow averaged spectrum is nearly a power law with index similar to that observed and depends on only one parameter namely the maximum temperature of the flow. The advantages and shortcomings of these mechanisms will not be examined here since they have been recently reviewed elsewhere (Rothschild et al 1983). We shall rather restrict ourselves to the study of the non-thermal mechanisms by pointing out that they can account for both the radio and X-ray emission with a single electron distribution.

Protheroe and Kazanas (1983) and Kazanas and Protheroe (1983) (hereafter PK and KP respectively) have presented such a non-thermal model for the origin of the relativistic electrons in AGNs and OSOs, based on the idea of first order Fermi shock acceleration (Bell 1978a,b; Blandford and Ostriker 1978; Axford, Leer and Scadron 1977). According to the model the radiating relativistic electrons result as secondaries in nuclear collisions of shock accelerated protons. The resulting electron spectrum, identical at high energies to that of the shock accelerated protons, is a power law of index Γ which depends only on the compression ratio, r, of the shock ($\Gamma = (r+2)/(r-1)$, which for sufficiently strong shocks is r=4, leading to an E^{-2} power law for the accelerated particles.) Although such an injection spectrum for the relativistic electrons reproduces the overall spectral energy distribution of these objects (i.e. approximately equal energy per decade) and it can account for the IR to UV part of their spectra, it leads to an underlying steady state electron distribution function (after Compton losses have been taken into account) steeper by one unit in the energy index i.e. $N_e \propto E^{-(\Gamma+1)} = E^{-3}$ which fails to reproduce the $\sim E^{-1.6}$ X-ray photon spectrum. Based on this mode, KP gave arguments suggesting an electron distribution function $\propto E^{-2}$ at lower energies breaking to E^{-3} at higher energies. Such a distribution function could then account for the observed spectra and when combined with γ-γ absorption at energies $E \geq 10$ MeV could also account for the spectrum of the diffuse gamma ray background in terms of AGNs.

In the present note it is indicated that such an electron distribution function, with the desired breaks, can be obtained under certain more general conditions if the reinjection, into the radiating plasma, of the e^+-e^- pairs produced by the γ-γ absorption is taken into account.

2. The e^+ e^- feedback

The self consistent treatment of relativistic plasmas i.e. the one that incorporates the self Comptonization of the internally produced radiation, as well as the possible feedback of e^+ e^- pairs, also internally produced, has only recently been undertaken (Lightman 1982; Svensson 1982). The above treatments however specialized to the case of relativistic thermal plasmas in which the bulk of the particles have a unique characteristic energy ~ kT, and the bulk of the radiation is also emitted at the same energy.

In the present note we examine the case of relativistic plasmas with power law distributions, which as argued earlier, may be more relevant in connection with the physics of AGNs. We then consider the effects of e^+-e^- pair production in such a plasma under the simplest possible conditions: Continuous injection of electrons in a given volume, and Compton losses as the major energy loss mechanism. Synchrotron losses are also considered but only as a means for producing the seed soft photons needed for the IC scattering. The differential electron injection spectrum is assumed to be a power law of index Γ i.e

$$Q_e(E) = K_e \ \gamma^{-\Gamma} \qquad \text{el cm}^{-3}\ \text{s}^{-1}\ \text{erg}^{-1} \qquad (1)$$

where γ is the Lorentz factor of the electrons assumed to be relativistic ($E = \gamma m_e c^2$, $\gamma>2$). Following PK, the steady state electron distribution will be given by

$$N_e(E) = \frac{1}{d\gamma/dt} \int_\gamma^\infty Q_e^{tot} \ (\gamma') \ d\gamma' \qquad \text{el cm}^{-3}\ \text{erg}^{-1} \qquad (2)$$

where $d\gamma/dt \propto \gamma^2$ is the rate of energy loss by an individual electron due to Compton losses in the Thomson limit (Blumenthal and Gould 1970) and $Q_e^{tot}(\gamma)$ is the total rate of electron injection into the system, including the feedback injection of e^+-e^- pairs due to γ-γ absorption. Since, according to our assumptions, these photons are due to IC of certain synchrotron seed photons (which are not important energetically), we can write, following PK,

$$Q_e^{tot}(\gamma) = Q_e(\gamma) + 2 \int 2\, Q_{IC}(E_\gamma)\ \delta\ (E_\gamma - 2\gamma)\ \phi_{\gamma\gamma}\ (E_\gamma)\ dE_\gamma \quad (3)$$

The first term of the RHS of eq(3) is the continuous direct electron injection, while the second is the term accounting for the e^+-e^- pair reinjection due to γ-γ interactions. $\phi_{\gamma\gamma}$ (E_γ) is the probability of absorption of an IC photon of energy E_γ, while the δ- function guarantees that the contribution to electrons of energy E_γ comes from photons of energy 2γ. The factors two account for the fact that two particles, of approximately equal energy (Bonometto and Rees 1971), are produced for each photon of energy E_γ, and also for the change in the energy interval, $dE_\gamma/d\gamma$, needed for particle conservation. $Q_{IC}(E_\gamma)$ is the IC emissivity given by

$$Q_{IC}\ (E_\gamma) = \int c n(\varepsilon) d\varepsilon \int N_e(\gamma) \frac{d\sigma}{d\gamma}\ (E_\gamma,\ \varepsilon,\ \gamma)\ d\gamma \quad (4)$$

$n(\varepsilon)$ is the soft (synchrotron) photon number density and $\frac{d\sigma}{d\gamma}$ $(E_\gamma, \varepsilon, \gamma)$ is the differential cross section for producing a high energy photon of energy E_γ in an IC scattering of a soft photon of energy ε with an electron of energy γ. The electron steady state distribution can then be obtained by solving the system of eqs (2),(3) and (4). This is an integral system of equations since the RHS of eq(3) depends, through $Q_{IC}(E_\gamma)$ on the unknown electron distribution $N_e(\gamma)$. Due to the complicated forms of the functions $\phi_{\gamma\gamma}$ (E_γ) and $d\sigma/d\gamma$ the solution to the system is precluded from being analytic. However, using the δ- function approximation for $d\sigma/d\gamma$ (Ginsburg and Syrovatskii 1964) and the step function approximation for $\phi_{\gamma\gamma}$ $(E_\gamma) = \theta$ $(E_\gamma - E_1)$ (both approximations are actually reasonable), an analytic solution can indeed be found. In the present note we shall restrict ourselves in presenting the solution and giving a qualitative justification of it, deferring the mathematical details and the numerical models to future work.

The fact that a unique spectrum, independent of the primary injection, is attained can be understood by looking at the behavior of the feedback term in eq(3). Neglect for the moment the existence of the feedback. If the injection spectrum is such as given by eq(1), then the steady state electron distribution function, assuming only Compton (and/or synchrotron) losses, will be $N_e(\gamma) \propto \gamma^{-p}$ where $p= \Gamma + 1$. Consequently the IC photons will also have a power law distribution with index $s=(p+1)/2= \Gamma/2 + 1$. Since these IC photons are the ones responsible for the feedback and since their energies $E_\gamma >> m_e$, the resulting $e^+ e^-$ pairs from the feedback will have a similar distribution of index s. One can now observe that $\Gamma = s$, (i.e. the primary Q_e, and the distribution of e^+-e^- pairs injected by the feedback process have the same index) only for $\Gamma = 2$. If $\Gamma > 2$ then $s < \Gamma$, while if $\Gamma < 2$ then $s > \Gamma$. The effect of the feedback is therefore to redistribute the electrons towards a $\Gamma = 2$ spectrum. Considering therefore the effects of the feedback at higher orders (i.e the feedback of the feedback etc.) one can see that the equilibrium spectrum is the one for which the feedback spectrum has an index $s \cong \Gamma \cong 2$, and equivalently, the steady state electron distribution function an index $p=s+1=3$. The validity of these arguments depends, of course, on whether the magnitude of the feedback is suficiently large so that the latter dominates the primary injection. Since the feedback action is essentially the redistribution of the high energy part of the electron spectrum, one would expect it to be important only if most of the energy is in the high energy part of the spectrum. This will indeed be the case if $\Gamma < 2$. This conclusion is similar to that of Bonometto and Rees (1971), who considered a similar case with δ-function electron injection at an energy $E_0 > E_1$. In the remaining of the paper we shall only consider the $\Gamma < 2$ case since the $\Gamma > 2$ case appears to be uninteresting.

Finally, to complete the discussion it is necessary also to consider the distribution function at energies $E<E_1$, for which it is assumed that $\phi_{\gamma\gamma}(E_\gamma) \equiv 0$. Eq(2) shows that from $\gamma \gtrsim 1$ to $\gamma = \gamma_1 \approx E_1$ the integral will be a constant since it is dominated by the feedback term which becomes effective only for $\gamma > E_1$. This would then lead to a spectrum of the form $N_e \propto (d\gamma/dt)^{-1} \propto \gamma^2$ for $\gamma < \gamma_1$, while it should be $N_e \propto \gamma^{-3}$ for $\gamma > \gamma_1$ as argued earlier. The exact spectrum is actually given by (Kazanas 1984)

$$N_e(\gamma) = C_e \begin{cases} \gamma^{-p} + F(p)\,\gamma^{-p_1} + F(p)F(p_1)\,\gamma^{-p_2} + \ldots + F(p)F(p_1)\ldots F(p_{i-1})\gamma^{-p_i} & \gamma>\gamma_1 \\ \gamma^{-p} + F(p)\gamma_1^{-(p_1-1)/2}\,\gamma^{-2} + \ldots + F(p)F(p_1)\ldots F(p_{i-1})\gamma_1^{-(p_{i-1}-1)/2}\,\gamma^{-2} & \gamma<\gamma_1 \end{cases} \quad (5)$$

C_e is an arbitrary normalization constant p_i is the power law index of the ith iteration: $p_i = (p-3)/2^i + 3$, where p is the index corresponding to the originally injected spectrum, i.e. $p = \Gamma + 1$. $F(p_i)$ are the amplitudes of each iteration given by

$$F(p_i) = (4/3)^{(p_i-3)/2}\ \frac{2^{-(p_i-3)/2}}{p_i-1}\ \frac{\int_{\varepsilon_m}^{\varepsilon_M} \varepsilon^{-1}\, d\varepsilon}{\int_{\varepsilon_m}^{\varepsilon_M} \varepsilon^{-(p_i-1)/2}\, d\varepsilon}$$

ε_m and ε_M are the minimum and maximum energies of the soft photon distribution in units of m_ec^2, assumed to be produced by the synchrotron radiation from the electrons of distribution N_e. The sum of the above series is shown in fig. 1. The bottom curve corresponds to the electron distribution with no feedback, while each subsequent curve shows the contribution of consecutively higher order feedback terms. As seen in the figure the series converges fairly fast and 3-4 iterations are sufficient to achieve the steady state index $p \cong 3$. For $\gamma < \gamma_1$ the spectrum also has the γ^{-2} form as argued heuristically.

Discussion - Conclusions

It has been shown that under the conditions of continuous power law electron injection, with Compton losses as the dominant loss mechanism, and γ-γ absorption of the resulting IC photons, the steady state electron distribution function aquires a unique form independent of the originally injected spectrum, provided that the latter has an index $\Gamma < 2$. The resulting distribution function is a power law with index $p = 2$ for electron energies smaller than the energy at which the γ-γ opacity becomes unity, and an index $p = 3$ for higher energies. Before however any conclusions are drawn from these results one should bear in mind that in deriving them it was implicitly assumed that: a) Compton losses dominate over synchrotron losses. This approximation, shown in PK to be valid for 3C273, effectively determines the importance of the feedback relative to the primary injection. If the contrary is true and a large fraction of the energy is emitted as synchrotron (at energies $< \gamma_1 m_e c^2$), the energy at which the feedback injection becomes more important than the primary one would shift to lower energies and might, under certain circumstances, become unimportant. b) Only first order IC scattering was considered. This assumption can be justified if the electron distribution cut off, γ_M, is sufficiently high that $\gamma_M \varepsilon_M \sim 1$ or $\gamma_M \gtrsim \gamma_c = 3.7\ 10^4\ B^{-1/3}$ (B in Gauss) c) The Thomson approximation for the electron scattering and losses was used (i.e $d\gamma/dt = \gamma^2 \int_{\varepsilon_m}^{\varepsilon_M} \varepsilon n(\varepsilon) d\varepsilon$). If $\gamma_M > \gamma_c$ or $\gamma_M \varepsilon_M > 1$, then for $\gamma > 1/\varepsilon_M$ $d\gamma/dt \approx \gamma^2 \int^{1/\gamma} n(\varepsilon) \varepsilon d\varepsilon$ (Rees 1967), and if $n(\varepsilon) \propto \varepsilon^{-s}$, then $d\gamma/dt \propto \gamma^s$. Therefore according to eq (2) $p=s+\Gamma-1$ and since $s=(p+1)/2$ $p=2\Gamma-1$ or $s=\Gamma$. The last relation implies that for sufficiently high γ, such that $\gamma\epsilon_M>1$, the feedback index, s, is identical to the primary injection index, Γ. Hence the steady state index, p, does depend on Γ and the feedback does not have the drastic effect it had in the Thomson limit (i.e. setting p=3). The assumptions concerning the electron injections at high γ were motivated and justified in an earlier work (PK). Finally the $\Gamma < 2$ assumption can be justified in terms of shock acceleration if the relativistic particle contribution to the pressure and/or losses soften the effective adiabatic index to allow compression ratios $\gamma > 4$ and hence spectra flatter than E^{-2} (Drury 1983, Ellison et al. 1981).

One can observe that the electron disribution function given in eq (5) under the above assumptions, can easily reproduce by synchrotron radiation the general characteristics of AGNs and QSOs from radio to UV even under the assumpton uniform magnetic fields and spatially homogeneous electron distribution. Of particular interest is the $F_\nu \sim \nu^{-1}$ IR to UV behavior observed in several objects (Glass et al 1982) reflecting the E^{-3} part of the electron distribution function. The X-ray spectra can then be accounted for in terms of IC scattering off this electron distribution function and they should steepen at higher energies to $\sim E^{-2}$ and eventually to $E^{-2.5}$ due to $\gamma\gamma$ absorption at energies such that $\tau_{\gamma\gamma}(E_\gamma) \geq 1$ as pointed out in PK and KP. Using the assumptions of Herterich (1974) the optical depth $\tau_{\gamma\gamma}(E_\gamma)$ can be approximated by

$$\tau_{\gamma\gamma}(E_\gamma) \approx 0.14\, L_{43}\,(1\text{-}10\ \mathrm{keV})\, R_{15}^{-1}\, E_\gamma^{\alpha-1}$$

and depends on only one parameter, the compactness L/R of the sources. (It is assumed that the X-ray photon index is $\alpha \approx 1.5$.) As already mentioned the condition $\tau_{\gamma\gamma}(E_\gamma) \approx 1$ gives effectively the energy γ_1 of the break of the spectral index. As shown in KP for a typical AGN luminosity L_X (1-10 keV) $\simeq 10^{43}$ erg s^{-1} the corresponding typical radius needed to provide agreement with the observations of the diffuse γ ray background is $R \simeq 10^{15}$ cm, in agreement with the observed time variability (Bassani and Dean 1981). In this case then, the condition $\tau_{\gamma\gamma}(E_\gamma) \simeq 1$ implies $E_\gamma \simeq \gamma_1 \simeq 10^2$ thus justifying the value of γ_1 used in this paper.

Finally there is a question concerning the photon - photon produced electron positron pairs. If, as presently considered, no escape of electrons from the system is possible, the continuously accumulated pairs would make the system infinitely thick in a very short time. An escape from the system has to be invoked to remove the electrons accumulated at low energies ($\gamma \simeq 1$). A jet, accretion onto the central object or annihilation offer some of the obvious alternatives. However, provided that the escape time is long compared to that of Compton losses, a condition easily met in these compact sources, all the above arguments concerning the higher energy electrons should hold, thus arguing and accounting for the uniqueness of AGN spectra.

I would like to acknowledge several stimulating discussions with Frank Jones, and several critical comments by Jim Felten and Alice Harding.

REFERENCES

Axford, W. I., Leer, E., and Scadron, G. 1977, 15th I.C.R.C., 2, 273

Bassani, L, and Dean, A. J., 1981, Nature, 294, 332.

Bell, A. R., 1978a, M.N.R.A.S., 182, 147.

-----------. 1978b, M.N.R.A.S., 182, 443.

Blandford, R. D., and Ostriker, J. P. 1978, Ap. J. (Lett.), 221, L29.

Blumenthal, G. R. and Gould, R. J. 1970, Rev. Mod. Phys., 42, 237.

Bonometto, J. and Rees, M. J. 1971, MNRAS, 152, 21.

de Bruyn, A. G. and Wilson, A. S. 1976, Astr. Ap., 53, 93.

Drury, L. O'C., 1983, Rep. Prog. Phys., 46, 973.

Ellison, D. E. Jones, F. C. and Eichler, D. 1981, Journal of Geophys. 50, 110.

Ginsburg, V. L. and Syrovatskii, S. I. 1964, "The Origin of Cosmic Rays". MacMillan, New York.

Glass, I. S., Moorwood, A. F. M. and Eichendorf, W., 1982, Ast. and Ap., 107, 276.

Herterich, K., 1974, Nature, 250, 311.

Jones, T. W., O'Dell, S. L. and Stein, W. A. 1974, Ap. J., 204, 187.

Katz, J. I. 1976, Ap. J., 206,910.

Kazanas, D., 1984, (in preparation).

Kazanas, D. and Protheroe, R. J. 1983, Nature, 302, 228.

Kellerman, K. I. 1966, Ap. J., 146, 621.

Lightman, A. P. 1982, Ap. J., 253, 842.

Meszaros, P., 1983, Ap. J. (Lett), 274, L13-L17.

Mushotsky, R. F., 1978, PhD thesis, UCSD.

Protheroe, R. J. and Kazanas, D. 1983, Ap. J., 265, 620.

Rees, M. J. 1967, MNRAS, 137, 429.

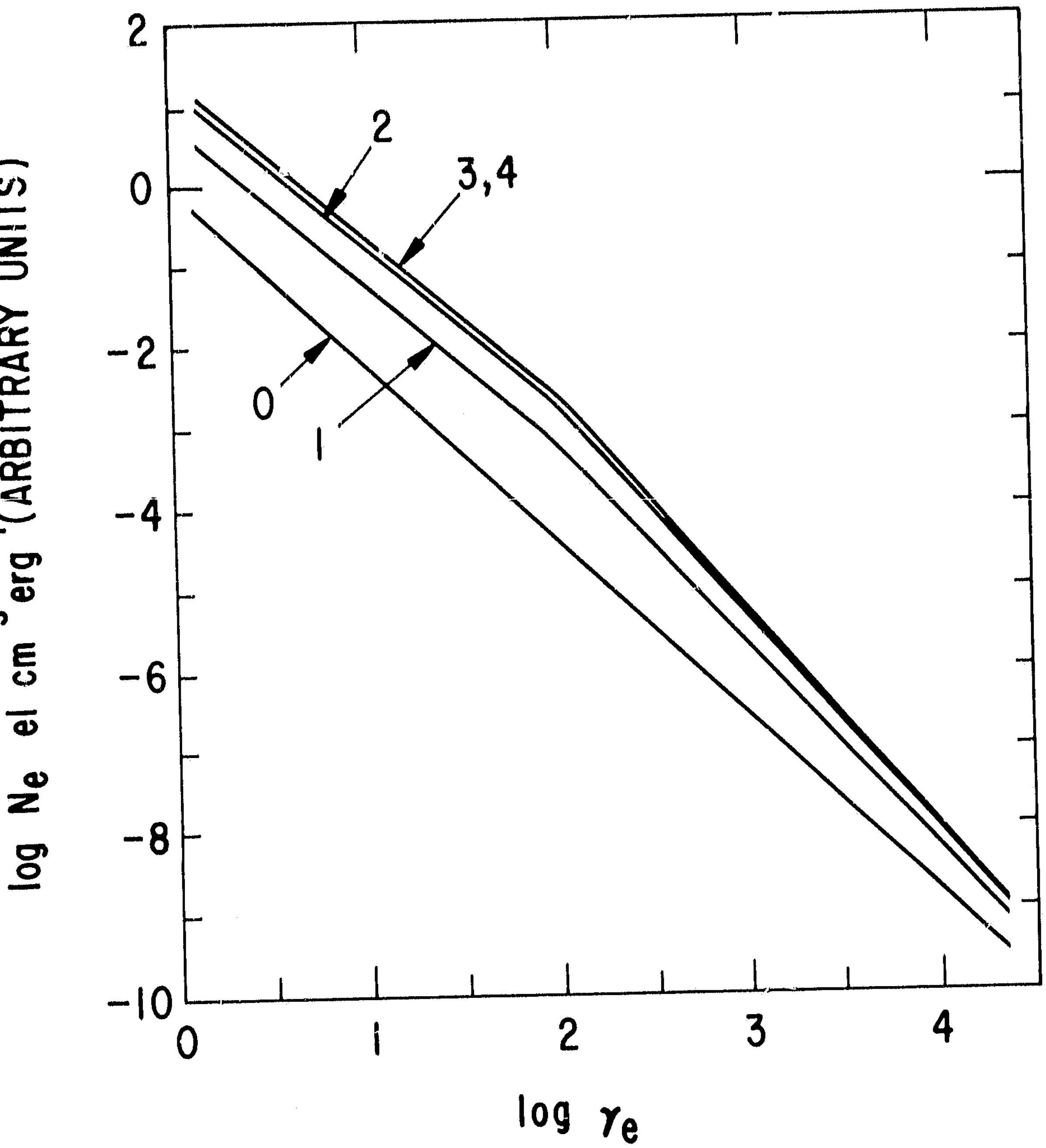
Rothschild, R. E., Mushotzky, R. F., Baity, W. A., Gruber, D. E., Matteson, J. L. and Peterson, L. E. 1983, Ap. J., 269, 423.

Shapiro, S. L., Lightman, A. P. and Eardley, D. M. 1976, Ap. J., 204, 187.

Svensson, R. 1982, Ap. J., 258, 335.

FIGURE CAPTION

The steady state electron distribution function $N_e(\gamma)$ at various iterations numbered by the numbers on the curves. The injection spectra has an index Γ = 1.2 with corresponding P = 2.2 i.e. $N_e(\gamma) = \gamma^{-2.2}$ (zero curve). The ε_m and ε_M were taken to be 10^{-6} and 10^{-4} respectively. while $\gamma_1 = 10^2$. The curves 1,2,3 represent successive iterations to the distribution function due to the photon-photon feedback. As shown 3-4 iterations are sufficient to achieve the steady state distribution.


2
0
-2
-4
-6
-8
-10
log N_e el cm^{-3} erg^{-1} (ARBITRARY UNITS)
0
1
2
3
4
log γ_e
2
3,4
0
1