THE UNIVERSAL SPECTRUM OF AGNs AND QSOs

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 then reproduce the general characteristics of AGN, QSO spectra from radio to X-rays. It also implies gamma ray emission from these objects consistent with the observations of the diffuse gamma ray background.

1. Introduction. One of the most striking observational features of AGNs and QSOs is the spectral distribution of their radiation, extending to over 10 orders of magnitude from radio to gamma rays with roughly equal energy per decade. This fact alone argues strongly for the non-thermal character of their radiation (Jones et al. 1974) although it has also been modeled as thermal emission from an accretion disk over a limited band pass extending ~ 1 order of magnitude in energy (Katz 1976; Malkan 1983). In addition statistical studies have indicated that the spectra of these objects in the IR to soft X-rays (Malkan 1984) and 2-50 keV band (Rothschild et al. 1983) can be well fitted by power laws of specific energy indices, $\alpha \simeq 1$ and $\alpha \simeq 0.65$ respectively. Most remarkably these indices appear to be independent of the luminosity and the external morphology of a particular source. To better appreciate this similarity one has to consider the large number parameters involved in determining the emission of these objects (Mass of the black hole; accretion rate; magnetic field; angular momentum; angle to the line line of sight etc.) and contrast it to the spectral diversity of another class of objects, namely stars, whose spectra are determined by a single parameter, namely their mass.

Protheroe and Kazanas (1983) and Kazanas and Protheroe (1983) (Hereafter PK and KP respectively) have tried to address this problem by arguing that the non-thermal electron distribution needed could result from 1st order Fermi shock acceleration and pointed out that the E^{-3} steady state (after Compton and synchrotron losses) differential particle spectra, predicted by the theory (Bell 1978a, b; Blanford and Ostriker 1978; Axford, Leer and Scadron 1977) could account for the overall energy distribution in the spectra of these objects. However, the X-ray spectra are considerably flatter, α = 0.5-0.8, (Rothschild et al. 1983) and hence the simplest model of a single powerlaw fails to account for the data. Within the simplest sychrotron self Compton model there should therefore be at least a break in the electron distribution

function from E^{-2} to E^{-3}.
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 model considered assumes only 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

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

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

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

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,

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

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

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

$n(\varepsilon)$ 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 $N_e(\gamma)$. 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), one actually can find an analytic solution to this system.

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 $N_e(\gamma) \sim \gamma^{-p}$ 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 $E_\gamma \gg m_e$, 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. The necessary condition for this is $\Gamma < 2$, and the effects of the feedback will be more important the lower the value of Γ and the higher the maximum energy to which the injection spectrum extends. This conclusion is similar to that of Bonometto and Rees (1971), who considered a similar case with δ-function electron injection at an energy $E_0 > E_1$.

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 $\gamma = \gamma_1 = E_1$ 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 $N_e \propto 1/(d\gamma/dt) \propto 1/\gamma^2$. while it should be $N_e \propto \gamma^{-3}$ for $\gamma > \gamma_1$ as argued earlier. The figure shows the analytic series solution to the system of eqs. (2)-(4). 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. (For details see Kazanas 1984).

2. Discussion and Conclusion. A mechanism has been presented which can produce an electron distribution function that can account for the overall spectral distribution of radiation of AGNs and QSOs and the specific slopes observed in the IR-UV and 2-50 keV bands. It is interesting to note that the necessary condition for this mechanism to

work (i.e. most of energy injected at $E >> m_e c^2$) is realized in the accretion shock model of Kazanas and Ellison (paper OG 8.1-7; these proceedings). This mechanism involves only one free parameter the compactness of the sources, L/R, whose mean value can also account for the diffuse gamma ray background in terms of AGNs. (KP 1983). Finally as pointed in KP the required form of the electron distribution function can be obtained even if $\Gamma \gtrsim 2$, if all electrons are produced as secondaries in relativistic p-p collisions, due to the cutoff of the injection spectrum for $E \lesssim 30$ MeV.

3. References

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

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.

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

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, Ap. J., 287, 112.

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

Malkan, M. A., 1983, Ap. J. 268, 582.

Malkan, M. A., 1984, "X-Ray and UV Emission from AGNs" eds. Brinkmann and Trumper, P. 121.

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

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

Figure: The steady state electron distribution function $N_e(\gamma)$ at various iterations numbered by the numbers on the curves. The injection spectrum has an index $\Gamma = 1.2$ with corresponding p = 2.2 i.e. $N_e(\gamma) = \gamma^{-2.2}$ (zero curve), while $\gamma_1 = 10^2$. The curves 1,2,3 represent successive iterations to the distribution function due to the photon-photon feedback.