THE ASTROPHYSICAL JOURNAL, 429:L53–L56, 1994 July 10

ON THERMAL COMPTONIZATION IN $e^{\pm}$ PAIR PLASMAS

GABRIELE GHISELLINI[1] AND FRANCESCO HAARDT[2,3]
Received 1994 February 16; accepted 1994 April 28

ABSTRACT

We study $e^{\pm}$ pair plasmas in pair equilibrium, which emit high-energy radiation by thermal Comptonization of soft photons. We find that the maximum luminosity to size ratio of the source (i.e., the compactness) depends not only on the hot plasma temperature, but also on the spectral index of the resulting Comptonized spectrum. In the observationally interesting range, sources of same compactness can be hotter if their spectrum is steeper. Instruments observing in the 50–500 keV energy range, such as OSSE on-board *CGRO*, and especially the future SAX satellite, can be more successful in detecting sources moderately steep, the flattest sources being characterized by an high-energy cutoff at too low frequencies. For any given pair of values of spectral index and temperature, Comptonization theory alone fixes the *ratio* of the compactnesses in hard and soft photons. However, if the source is pair dominated, the absolute values of the two compactnesses are fixed. Therefore there is a one-to-one correspondence between the physical parameters of the source (the compactnesses in soft and hard photons) and the observable quantities (spectral index and temperature). This correspondence can be extremely useful in interpreting the physical behavior of the sources, especially during variations, and can help discriminating between models for the high-energy emission of compact sources.

Subject headings: galaxies: Seyfert — gamma rays: theory — plasmas — radiation mechanisms: thermal — X-rays: general

1. INTRODUCTION

The recent observations of OSSE on the *Compton Gamma-Ray Observatory* have shown a break or an exponential cutoff in the high-energy X-ray spectrum of Seyfert galaxies (Maisack et al. 1993, Cameron et al. 1994, Madejski et al. 1994).

These observations can be interpreted in the framework of thermal Comptonization models, even if a nonthermal origin of the high-energy radiation cannot be ruled out (Zdziarski 1994). Thermal models have been recently successful in explaining the X-ray background as the sum of the emission of Seyfert galaxies, even if it is not yet clear which type of Seyfert galaxies contribute the most (see, e.g., Madau, Ghisellini, & Fabian 1993; Zdziarski, Zycki, & Krolik 1993).

The fact that there exists a relatively narrow range of temperatures of emitting plasmas in active galactic nuclei (AGNs) can be understood on the basis of the thermostat effect of electron-positron pairs, after the classic papers of Bisnovatyi-Kogan, Zel'dovich, & Sunyaev (1971), Svensson (1982, 1983, 1984), Lightman (1982) and Zdziarski (1985).

The main result of these studies is that, for any given luminosity to size ratio of the source, there exists a maximum temperature at which the emitting plasma can be in steady state. If the temperature is greater than this maximum limit, photon-photon, photon-particle and particle-particle collisions produce pairs that cannot annihilate at the same rate. For the same reason, increasing the luminosity to size ratio (the compactness), the temperature is bound to decrease.

Furthermore there are indications that the high-energy emission of AGNs in general, and Seyfert galaxies in particular, comes from the inner regions surrounding the black hole, and that the luminosity is greater than few percent of the Eddington limit (Padovani 1989; Done & Fabian 1990). We therefore believe that AGNs are characterized by a relatively narrow range of compactnesses and, hence, of temperatures.

However, there can be differences among different AGNs, and, most notably, there are differences in the spectral indices of their X-ray emission. Although the 2–10 keV spectral indices α_x of Seyfert 1 galaxies and quasars have a small scatter around the mean value, α_x ranges from 0.4 to values steeper than 1 (Turner et al. 1990; Comastri et al. 1992).

In this paper we investigate the behavior of sources in pair equilibrium characterized by different spectral indices by assuming thermal Comptonization of soft photons as the main radiation mechanism. In the framework of these models different spectral indices are due to different ratios L_s/L_h between the luminosity in soft photons and the luminosity produced by the hot particles. We therefore investigate the equilibrium states of hot plasmas characterized by different compactnesses and different L_s/L_h ratios.

The main results of this work are a relation between the spectral index α_x and the temperature T of plasmas in pair equilibrium, and a one-to-one correspondence between α_x, T and the compactnesses in hard and soft photons.

These results can have important consequences:

1. For predicting a correlation between spectral index and cutoff energy in pair dominated AGNs, in the sense already observed for NGC 4151 (Jourdain et al. 1992; Maisack et al. 1993; Zdziarski, Lightman, & Maciolek-Niedźwiecki 1993) and IC 4329A (Madejski et al. 1994);

2. For predicting the high energy emission, in the OSSE range, of sources with different spectral indices in the 2–10 keV band;

3. For interpreting the behavior of the overall spectrum of individual sources during spectral and flux variations.

[1] Osservatorio di Torino, Pino Torinese, 10025 Italy;
E-mail: 32065 : : ghisellini; ghisellini@to.astro.it.
[2] ISAS/SISSA, Via Beirut 2–4, 34014 Trieste, Italy;
E-mail: 38028 : : haardt; haardt@tsmi19.sissa.it.
[3] Postal address: STScI, 3700 San Martin Drive, Baltimore, MD 21218;
E-mail: 6559 : : haardt; haardt@kepler.stsci.edu.

2. THERMAL COMPTONIZATION AND PAIR PRODUCTION

Thermal Comptonization has been extensively studied in the past (see, e.g., Sunyaev & Titarchuk 1980; Pozdnyakov, Sobol', & Sunyaev 1983).

We assume that soft photons are homogeneously distributed throughout a sphere of radius R, with a diluted blackbody spectral distribution of dimensionless temperature $\Theta_{BB} \equiv kT_{BB}/(m_e c^2)$. The sphere is homogeneously filled with hot plasma, with dimensionless temperature Θ, producing, via Comptonization, a luminosity L_h corresponding to a compactness $l_h \equiv L_h \sigma_T/(Rmc^3)$ where σ_T is the Thomson cross section. Analogously, l_s is the compactness of the soft photon source.

The scattering optical depth, τ_T, and the temperature, Θ, of the hot plasma uniquely determine the Comptonized photon energy distribution, characterized by a power law and a cutoff at $h\nu/(m_e c^2) \sim \Theta$. Therefore we can treat the temperature Θ and the spectral index α (instead of Θ and τ_T) as the two variables.

Although sufficient to completely determine the shape of the Comptonized photons, α and Θ do not yield its normalization, but only the amplification factor, i.e., the ratio l_h/l_s. Symbolically

$$(\alpha, \Theta) \rightarrow l_h/l_s \tag{1}$$

Note that the reverse is not true, since the same amplification can be achieved with a range of values of α–Θ.

In order to determine the absolute value of l_h and l_s one has to consider the effects of $e^{\pm}$ pair production.

The main result of hot plasma studies is that the compactness of a source in equilibrium at a given temperature cannot reach arbitrary large values. In fact, as long as the compactness is very small, an increase in the heating rate corresponds to an increased mean energy per particle, and therefore to an increased temperature. But when the temperature starts to be relativistic, pair production is important, and the number of particles in the thermal bath increases. Since the available energy is now shared among more particles, the temperature in this regime decreases as the heating rate (the compactness) increases. The equilibrium and steady state corresponds to pair balance: pairs are destroyed at the same rate at which they are created. For any given temperature, there is a *maximum* compactness allowing pair equilibrium, and for any given compactness, there is a *maximum* allowed temperature. The precise value of the function $l_{h,\max}(\Theta)$ depends on the detail of the emission mechanism (bremsstrahlung, Comptonization, cyclosynchrotron, and so on). Hereafter we use the symbol l_h to indicate the maximum allowed value $l_{h,\max}$.

If the main radiation mechanism is thermal Comptonization, any pair of values of α and Θ determines the maximum allowed compactness l_h. Symbolically we have

$$(\alpha, \Theta) \Leftrightarrow (l_h, l_s) \tag{2}$$

Note that now there is a one-to-one relation between the physical parameters of the source (l_h and l_s) and the observable quantities (α and Θ).

Following Zdziarski (1985, hereafter Z85) we calculated $l_h(\Theta)$ for different values of α, limiting ourselves to temperatures $\Theta < 10$ ($kT < 5$ MeV), where particle-particle and particle-photon pair production processes are less important than photon-photon interactions, and can therefore be neglected. The formulae used are described in Z85; the Comptonized spectrum is described as the sum of a power-law spectrum with an exponential cutoff at Θ and a Wien spectrum at Θ: $l_h = l_{pl} + l_W$. The formulae of Z85 well describe the Comptonized spectrum at high energies, but give a poor representation of the spectrum at low energies. To derive l_h for $\alpha > 1$ and l_s (to be derived by photon number conservation), a more detailed description of the Comptonized spectrum at low energies is required.

We therefore computed the thermally Comptonized spectra in spherical geometry by means of the full relativistic kernel (Jones 1968; Coppi & Blandford 1990). This gives the exact value l_h/l_s for any (τ_T, Θ). We then computed a lower integration limit, x_1, for equation (1) in Z85 so that the integrated photon spectrum and luminosity coincide with the exact values. We checked that, with the given τ_T and Θ, the spectral indices used following the prescription of Z85 were correct. We used $kT_{BB} = 10$ eV and neglected, for simplicity, pair escape. Note that in the absence of pair escape there is an absolute maximum in the allowed temperature ($\Theta_{\max} = 24$) derived considering particle-particle interactions.

Our calculations are presented in Figure 1. As can be seen the curves $l_h(\Theta)$ have a sort of pivot at $\Theta \sim 1$, being flatter for flatter spectral indices.

To qualitatively understand this behavior, let us consider first a fixed value of Θ in the region corresponding to $l_h > 1$. As $\Theta < 1$, the only photons effective in pair production are in the Wien tail of the spectrum (see e.g., Fig. 4*a* of Z85).

Furthermore, if $\tau_T > 1$, simple radiative transfer assures that the compactness of the Wien component is fixed (it depends only on Θ), independently of τ_T. Increasing the total compactness then means to increase the compactness of the power-law component. But the two compactnesses are related by the value of τ_T: their ratio l_{pl}/l_W decreases as τ_T increases (more photons are driven to the Wien peak). Only a lower τ_T (i.e., steeper α) therefore allows a greater compactness of the power-law component.

Consider now the region corresponding to $l_h < 1$. In this case both the total luminosity and the pair production process are determined by l_{pl}, l_W playing no role. For fixed Θ, l_h can increase if

1. the new equilibrium state yields a greater τ_T and therefore a flatter spectral index. In this case the luminosity is increased at high energies increasing the pair production rate, which in turn yields the required increased τ_T.
2. the new equilibrium state yields a much lower value of τ_T and a much steeper spectrum. In this case the luminosity is increased at low energies and decreased at high energies, the pair production rate is decreased, and the corresponding τ_T decreases.

The first solution gives $\alpha < 1$ while the second one yields $\alpha > 1$. Although both these solutions are consistent with pair balance and Comptonization, the latter one exists only in a range of Θ. This range becomes larger for small values of the minimum energy of the Comptonized spectrum x_1 (where most of the luminosity is for $\alpha > 1$). For the adopted Θ_{BB}, the two solutions exist only in the small range $1 < \Theta < 2$, as shown in Figure 1.

Figure 1 shows that in the interesting (from the observational point of view) parameter range $0.1 < \Theta < 1$ pair dominated sources with same compactness should show a clear correlation between the spectral index and the cutoff energy: the flatter the spectral index, the lower the temperature.

Note that, as shown in Figure 1, the maximum possible

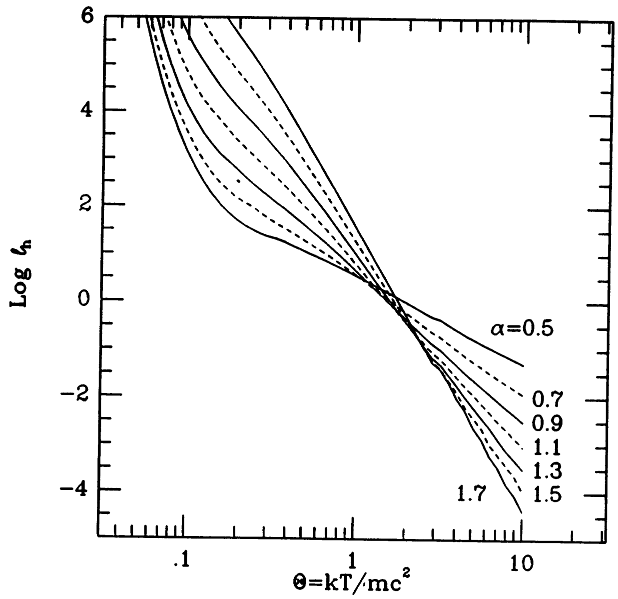

FIG. 1.—For any given temperature $\Theta \equiv kT/(m_e c^2)$ there exists a maximum possible compactness l_h of a plasma in pair equilibrium. The exact shape of the function $l_h(\Theta)$ depends on the spectral index resulting from the Comptonization process. Flatter spectral indices correspond to flatter $l_h(\Theta)$. Note that the curves (the labels indicate the value of the spectral index) cross for $l_h \sim 1$. For $l_h > 1$, sources with the same compactness have larger temperatures if their spectrum is steeper, and vice versa.

compactnesses for $kT \sim 50$ keV are extremely large, but these corresponds to completely pair dominated sources: if the hot emitting plasma has also a "normal", electron-proton component, the compactness can be smaller (or the temperature can be smaller than shown in Fig. 1, for the same compactness).

3. "MAPPING"

Thermal Comptonization together with pair plasma theory gives a one-to-one relation between $\alpha - \Theta$ and $l_s - l_h$. This means that we can "map" the plane $\alpha - \Theta$ into the plane $l_s - l_h$ (or equivalently $l_h/l_s - l_h$), and vice versa.

This "mapping" links physical parameters, such as the soft and the hard compactness, which completely characterize the source, with observable quantities, such as the spectral index and cutoff energy.

Figure 2 shows the results. In the "starvness-compactness" plane (i.e., $l_h/l_s - l_h$) we have mapped the "temperature-spectral index" plane, plotting curves for constant Θ and for constant α. We have restricted our analysis to the range which is observationally interesting (i.e., $0.5 < \alpha < 1.5$ and $0.1 < \Theta < 1$ corresponding to $51 < kT < 511$ keV).

It can be seen that l_h/l_s is not exactly constant for a given spectral index, but it has some weak dependence also on the temperature. Moving along a curve with constant Θ in the direction of steeper α we have that l_h/l_s decreases (as expected), while l_h increases (as explained in the previous section, and also shown in Fig. 1).

In this plane it is very easy to see what the equilibria states are when the source varies. For instance, suppose that a source initially in point labeled *A* in Figure 2 increases its power (l_h) by a factor 3. The compactness in soft photons, l_s, can either remain constant or vary together with l_h. The latter case may indicate that there is some feedback between the hot plasma producing the hard luminosity and the relatively cold plasma producing the seed photons, as in a cold disk illuminated by a hot corona.

The final states in the two cases are labeled B and C in Figure 2. As can be seen, point B corresponds to a temperature lower by a factor 1.5 and slightly steeper spectral index α, while point C corresponds to an even lower temperature (factor 2) and a flatter α. All the possible intermediate cases $5 < l_h/l_s < 15$ are between points B and C.

Another possibility is that the soft compactness varies even without any change in l_h. This is possible only if reprocessing (as a source of soft photons) is not important. Point labeled D corresponds to the final state of the source initially in A, after an increase by a factor 3 of l_s. The resulting equilibrium temperature is larger by a factor 1.2 and the spectrum has steepened.

In conclusion, knowing how the spectral index and the temperature change, one can know if l_s is bound to follow the variation of l_h. This is extremely important, as we can test models in which an important role is played by reprocessing of the high-energy radiation by cold matter located near the hot gas.

4. DISCUSSION

One of the main results of pair plasma studies is that the maximum compactness allowed by pair equilibrium decreases as the temperature increases. This however refers to sources with *fixed* spectral index, which roughly corresponds to fixed l_h/l_s.

We have shown that, from thermal Comptonization and pair plasma theories, one can derive a one-to-one correspondence between the observable quantities α and kT and the physical parameters l_h and l_s. The knowledge of any two of these four quantities univocally determines the other two.

The spectral behavior of a varying X-ray source depends on whether the ratio l_h/l_s or l_s remains constant when l_h varies. If

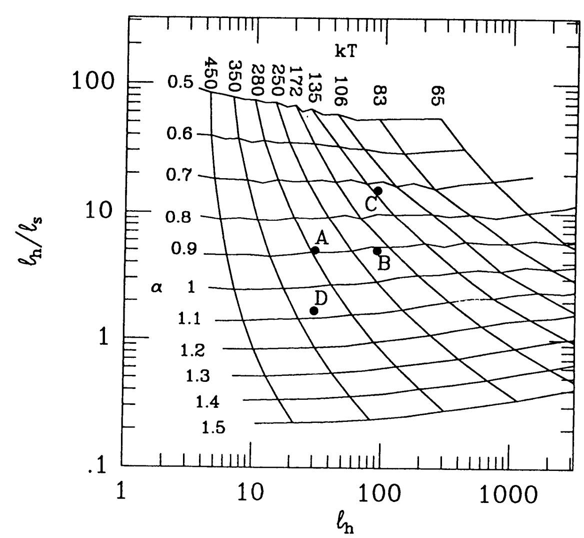

FIG. 2.—In the plane l_h/l_s vs. l_h (the starvness vs. hard compactness plane) we have drawn the curves for constant Θ and for constant α. The temperature increases from right to left, α increases (the spectrum steepens) from top to bottom, as labeled. As illustration, consider a source, initially in point A, which increases l_h by a factor 3. Its final equilibrium state will be between points B and C, if l_s remains constant or increases by the same amount of l_h. If, instead, l_s increases by a factor 3 without variations in l_h, the final equilibrium state will correspond to the point labeled D.

l_h/l_s is constant, the spectral index slightly steepens for increasing hard compactness and the temperature decreases. If l_s remains constant, the spectral index flattens for increasing l_h and the temperature decreases by a larger amount.

Observationally, there are indications that in some sources, during large variations of the X-ray flux, the X-ray spectral index remains approximately constant (e.g., Nandra et al. 1991), or slightly steepens (e.g., Yaqoob & Warwick 1991). This indicates that l_h/l_s is nearly constant during variations, strongly favoring models in which the soft component is dominated by the reprocessed flux (see, e.g., Haardt & Maraschi 1991). This in turn would imply the presence of cold matter [cloudlets (Celotti, Fabian, & Rees 1992; Sviron & Tsuruta 1993) or a cold accretion disk (Lightman & White 1988; George & Fabian 1991, Matt, Perola, & Piro 1991)] very close to the illuminating X-ray source. The above conclusion does not depend strictly on the importance of pairs, which instead can fix the temperature and the temperature change during variations of the source.

Observations of the cutoff energy of the X-ray spectrum are of crucial importance to establish if a source is pair dominated, and directly yield an upper limit on the compactness as illustrated in Figure 1. In addition, if variations of the flux correspond to variations of the high-energy cutoff as illustrated in Figure 2, we can derive the compactness of the source, not only an upper limit, and therefore the size of the emitting region. Hence it is very important to coordinate observations in the 2–10 keV band (which should yield the spectral index) and in the 50–500 keV band (which should yield the value of the cutoff energy). A good opportunity to pursue this program is presently offered by ASCA and OSSE missions, and in future, by the SAX satellite.

If a class of sources, such as Seyfert galaxies, are pair dominated with similar compactnesses, there should be a correlation between spectral index and temperature. In the range of compactness between 10 and 100, steeper spectra should correspond to larger temperatures. For $l_h = 100$, the maximum temperature is 70, 200, and 400 keV for spectral indices $\alpha = 0.5$, 1, and 1.5, respectively.

At present, only two Seyfert galaxies have their spectral index and cut off energy reliably measured, i.e., NGC 4151 and IC 4329A, and it is encouraging that the differences in their α_X and kT are in the sense discussed in this paper. NGC 4151 has $\alpha = 0.5$ and $kT \sim 50$ keV, while IC 4329A has $\alpha \sim 1$ and $kT > 150$ keV.

The correlation discussed in this paper should be taken into account when interpreting the X-ray background as due to Seyfert galaxies (and quasars) of different spectral indices, since for each α a different maximum temperature is indicated.

Finally, it is worth to point out that if a source has a flat α_X in the 2–10 keV band, it may have a cutoff at relatively small energies, and therefore it may be invisible in the 100–200 keV band (i.e., the OSSE band). On the other hand, very steep sources ($\alpha_X > 1$) have a very small flux in the OSSE band, and are therefore difficult to detect even if the cutoff energy is large. As a consequence, the probability to detect sources at 100 keV should peak for sources moderately steep ($\alpha_X \sim 1$) in the 2–10 keV band.

REFERENCES

Bisnovatyi-Kogan, G. S., Zel'dovich, Ya. B., & Sunyaev, R. A. 1971, AZh, 48, 24 (Soviet Astr.–AJ, 15, 17)
Cameron, R. A., et al. 1994, Proc. of the Compton Symp., ed. N. Gehrels, in press
Celotti, A., Fabian, A. C., & Rees, M. J. 1992, MNRAS, 255, 419
Comastri, A., Setti, G., Zamorani, G., Elvis, M., Giommi, P., Wilkes, B. J., & McDowell, J. C. 1992, ApJ, 384, 62
Coppi, P. S., & Blandford, R. D. 1990, MNRAS, 245, 453
Done, C., & Fabian, A. C. 1990, MNRAS, 240, 81
George, I. M., & Fabian, A. C. 1991, MNRAS, 249, 352
Haardt, F., & Maraschi, L. 1991, ApJ, 380, L51
Jones, F. C. 1968, Phys. Rev., 167, 1159
Jourdain, E., et al. 1992, 256, L38
Lightman, A. P. 1982, ApJ, 253, 842
Lightman, A. P., & White, T. R. 1988, ApJ, 335, 738
Madau, P., Ghisellini, G., & Fabian, A. C. 1993, ApJ, 410, L10
Madejski, G., et al. 1994, ApJ, submitted
Maisack, M., et al. 1993, ApJ, 407, L61
Matt, G., Perola, G. C., & Piro, L. 1991, A&A, 247, 25
Nandra, K., Pounds, K. A., Stewart, G. C., George, I. M., Hayashida, K., Makino, F., & Ohashi, T. 1991, MNRAS, 248, 760
Padovani, P. 1989, A&A, 209, 27
Pozdnyakov, L. A., Sobol', I. M., & Sunyaev, R. A. 1983, Ap. Space Sci. Rev., 2, 189
Sviron, R., & Tsuruta, S. 1993, ApJ, 402, 420
Sunyaev, R. A., & Titarchuk, L. G. 1980, A&A, 86, 121
Svensson, R. 1982, ApJ, 258, 335
———. 1983, ApJ, 270, 300
———. 1984, MNRAS, 209, 175
Turner, T. J., Weaver, K. A., Mushotzky, R. F., Holt, S. S., & Madejski, G. M. 1990, ApJ, 381, 85
Yaqoob, T., & Warwick, R. S. 1991, MNRAS, 248, 773
Zdziarski, A. A. 1985, ApJ, 289, 514 (Z85)
———. 1994, in Proc. 2d Compton Symp., in press
Zdziarski, A. A., Lightman, A. P., & Maciolek-Niedźwiecki, A. 1993, ApJ, 414, L93
Zdziarski, A. A., Zycki, P. T., & Krolik, J. H. 1993, ApJ, 414, L81