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Pairs in Compact Objects – Clues to Particle Acceleration

ABSTRACT

Electron-positron pairs are created by photon-photon collisions in compact objects such as Active Galactic Nuclei and Galactic Black Hole sources. The production of the pairs and their radiation change the emergent spectrum to make it steeper than the primary spectrum emitted by the accelerated electrons. Recent evidence for a reflected component – radiation scattered back by the accretion disc – causes emitted the spectrum to be further changed and to resemble the observed spectrum. Although this allows us to understand the observed radiation better, it masks the operation of the electron accelerator.

INTRODUCTION

The spectrum and variability of Active Galactic Nuclei (AGN) and Galactic Black Hole sources are the best handles we have on the electron population in these objects, and thus of the processes which accelerate the electrons. Understanding these processes should eventually give us a much clearer picture of the operation of the central engine.

The most rapid variability observed so far is in the X-ray band (*e.g.* Tennant [13]; Kunieda [9]), which suggests that it is in this band that we see deepest into AGN and similar sources. Simultaneous optical and X-ray observations of the rapidly X-ray varying nucleus of the nearby Seyfert Galaxy NGC4051 by Done (3) show less than 1 per cent variations in the optical band while the X-ray flux changed by a factor of two. This means that the region emitting the optical flux must be at least 10 times larger than the X-ray emission region, since the varying X-ray flux must correspond to a varying electron population in the region. This would produce a detectable, variable, Compton-scattered flux in the optical if there were a significant energy density of infrared and optical photons in the X-ray emission region. For these reasons, the discussion in most of this paper is concentrated on the X-ray emission in AGN and on what it implies for the radiation and particle acceleration processes.

The X-ray spectra of AGN (and of Galactic Black Hole candidates) are hard. There is a turnover in the spectrum at 100 – 2000 keV, giving what is called the 'MeV turnover' in AGN. This has suggested to many of us that the central engine is responding to the electron rest mass; the turnover is not a coincidence of parameters but something basic which is common to all the objects. There are many detailed ways in which this can occur, but in general we can predict that electron-positron pairs are common. The reasons for this are discussed in the next Section, together with some of the 'simple' attempts made to explain the overall X-ray spectrum using pair models.

Another, more complicated, way in which pairs might be involved is through what has been termed 'pair loading'. This is outlined in the following part. It involves considerable feedback on the acceleration process. The problem of so-called 'dead' electrons is also outlined. It concerns what happens to electrons that have cooled. They cannot just accumulate in the source or, through Compton scattering, they produce observable effects on the spectrum.

Many of the models for the spectrum of the X-ray emission regions in AGN produced so far are not able to account simply for the apparently standard power-law continuum observed over the 1 – 100 keV band (*e.g.* Turner [14]). The energy index of the spectrum $\alpha \sim 0.7$. Pair models for example generally predict a spectral index of 0.9 and so were appearing to be ruled out. Recent work however on the observed X-ray spectrum indicate that it consists of both 'direct' and 'reflected' components (Pounds [11]; Matsuoka [10]). The direct component does have a spectrum of about 0.9, so reviving the pair models (Zdziarski [15]). This is discussed in the final Section, with further comments on the particle acceleration process.

PAIRS AND THE COMPACTNESS PARAMETER

The general picture that is building up for the central engine of AGN is of a single massive compact object, a black hole, powered by accretion (or possibly by extraction of spin energy in some objects). The accretion flow is probably in the form of an accretion disc with a quasi-blackbody spectrum. The temperature of the disc material is then a few hundred thousand degrees.

The observational evidence for this picture is principally the strong variable X-ray component, which carries several tens per cent of the total power in many objects. (The work of Terlevich and others has shown that extreme stellar processes – multiple supernovae in dense gas – may simulate many of the properties seen in the optical and UV spectra of AGN.) The X-ray spectra are hard, as mentioned before, and strong variability, with a factor of 2 change in an X-ray luminosity of $\sim 10^{42}\,\mathrm{erg\,s^{-1}}$ being observed on a timescale of 300s (Matsuoka [10]) or even $\lesssim 50\,\mathrm{s}$ (Kunieda [9]). There is also a 'soft excess' observed in the spectrum below 1 keV which is identified with the accretion disc (Arnaud [1]; Turner [14]).

Most AGN that have been well-studied in the X-ray band appear to have a 2 – 10 keV spectral index of about 0.7. Their spectra also appear to turnover at about an MeV (although the data here are sparse and not very reliable). This raises the questions of why 0.7 and why an MeV? What we need to know is whether these are fundamental questions or simply the result of hard radiation being produced in a compact region.

One way in which this has been tackled is to search for mechanisms that give the observed spectrum in a robust manner from some simple input parameters. If successful, then the spectral shape of an AGN is not particularly informative about the fundamental workings of the central engine. The essential ingredients of most such models are soft photons and relativistic electrons. The soft photons may be from the accretion disc, which has a temperature close to the blackbody value, $kT_b = (L/R^2\sigma_{SB})$ where R is the size of the emission region. The relativistic electrons are due to some acceleration process. Since the protons in an accretion flow may attain energies up to m_pc^2, then it does not seem unreasonable that electrons are accelerated to high Lorentz factors, γ_{max}. Inverse Compton scattering of the soft photons by the electrons then leads to a hard spectrum extending to gamma-ray energies.

Superficially, this does not seem to account for a 0.7 index power law or an MeV turnover. As the electrons lose energy, they do create a steep electron spectrum which makes the photon index 0.5, but not 0.7. However, if the source is compact, then the gamma-rays can collide with the X-rays to produce electron-positron pairs. These then radiate so that the hardest radiation is degraded through a cascade of pairs and reprocessed into softer radiation. The threshold for the process is about an MeV, so a deficit of higher energy gamma-rays is expected and the MeV turnover can form.

The compactness of the region is defined in terms of the ability to make pairs. Basically, pairs are produced if the probability of photon-photon collisions is high. This is measured by the optical depth,

$$\tau_{\gamma\gamma} = n_\gamma \sigma_{\gamma\gamma} R,$$

where the X-ray photon density $n_\gamma > L/R^2 c m_e c^2$ and the cross-section $\sigma_{\gamma\gamma} \sim 0.2\sigma_T$. σ_T is the Thomson cross-section. Consequently, significant reprocessing of the power in the source occurs when the (dimensionless) compactness parameter,

$$\ell = \frac{L}{R}\frac{\sigma_T}{m_e c^3} \gtrsim 5.$$

This limit is exceeded by many AGN (Fig. 1).

The 'secondary' radiation from the pairs steepens the emergent X-ray spectrum at the expense of the gamma ray spectrum. Although it acts in the right sense to agree with the observations, detailed studies (Lightman [8]; Done [2]) have shown that pair production does not simultaneously give $\alpha \sim 0.7$ and an MeV turnover. Generally, if $\alpha \sim 0.7$ then there are too many gamma-rays, and if there is an MeV turnover, then $\alpha \gtrsim 0.9$. There is only a very narrow part of the parameter space ($\ell \sim 30$ and $\gamma_{max} \sim 200$) where some agreement is found with both the X-ray and gamma-ray spectra. Instead, the input electron spectrum may have the 'right' shape to produce the observed photon spectrum. All of these solutions appear to put the onus on the acceleration process for understanding the spectrum. I say appear, since there is another solution, to which I return later.

Another way in which the MeV turnover can be explained by pairs is to rely on 'pair loading' (Done [4]; see also Cavaliere [5]; Svensson [12]). This means that the pairs apply feedback to the acceleration process to cause the MeV turnover. To see how this might happen, consider that the acceleration process works on all the particles on the region. Then, if the available power is limited, as is likely, the production of pairs causes more particles to be accelerated and so the mean particle energy to drop, until a balance is reached. This tends to occur when the photon spectrum turns over around an MeV. It does not however appear to explain the spectral index in any simple manner.

A further problem that is generally ignored in discussions of compact hard sources is the 'dead electron' problem. This is the accumulation of cooled electrons (or pairs) which have lost their energy to radiation. If the Thomson depth in such pairs exceeds unity, which is easily attained, then electron scattering of hard radiation by the dead electrons produces features of characteristic shape – which are not observed. For example, a Thomson depth of τ_T in dead electrons will cause a break at an energy of $\tau^{-2} m_e c^2$, or at less than 20keV if $\tau > 5$. The standard way of overcoming this problem is to argue that there are few electrons in the source and that they are rapidly re-accelerated when on losing their energy. This does not help in a compact hard source since this just creates more electrons (and positrons) from photon-photon collisions. Nor does pair loading provide much improvement. The only solutions that we can devise (Done [4]), apart from that discussed in the next Section, are to argue that the cooled electrons are strongly clumped in the source, so that the covering fraction is low, to

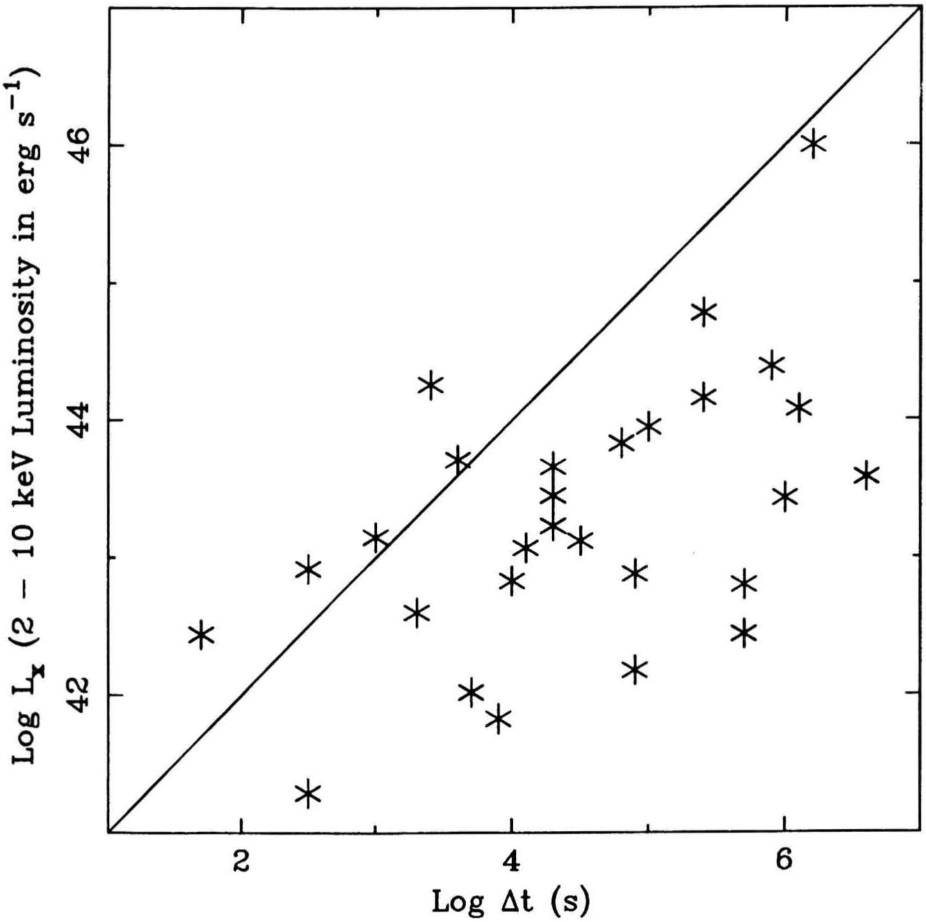

Figure 1. X-ray luminosity plotted against 2-folding variability timescale from Done (2). The diagonal line corresponds to $\ell = 5$ and is based only on the 2 – 10 keV luminosity. If, as is likely, the spectra extend to an MeV, then the line moves down by about a factor of 5 in luminosity. Pairs are then expected in most of the sources.

make the accelerator move rapidly or to appeal to rapid variations. In the last two possibilities, the source may just switch off once it has filled with electrons.

THE REFLECTED COMPONENT

The soft excess emission in AGN, if quasi-thermal, suggests that there is an optically-thick, cool ($T \sim 10^5$ K) accretion disc present in the central engine. The hard X-rays incident onto such material will be photo-absorbed and electrons scattered, creating a reflection spectrum. At low energies (less than about 5 keV) few X-rays will be scattered back into our line of sight because the photoelectric absorption cross-sections of disc matter are so high. Only above about 10 keV is there a substantial albedo of about 30 per cent. It drops again above about 100 keV since the Compton effect significantly reduces the energy of back-scattered photons. For photons between 7.1 and about 9 keV there is a strong chance of absorption by iron ions, which results in the emission of a fluorescent photon at 6.4 keV. The net reflected spectrum is then one of rising flux below 10 keV, with a strong iron line at 6.4 keV, bending over to follow the incident spectrum between about 30 and 100 keV and falling off at higher energies.

The observer sees a combination of the direct spectrum and the reflected spectrum. This predicted spectrum (Guilbert [6]; Lightman [7]) has now been confirmed by observations with the GINGA satellite (Pounds [11]; Matsuoka [10]), which show the iron line and the beginning of the relection hump above 10 keV. The interesting point here about the multi-component spectrum is that although the observed energy index is about 0.7, the addition of the flat reflection spectrum to the direct spectrum means that the direct spectrum must be steeper than the observed one. The required spectral index is now $\alpha = 0.9$, not 0.7, and so the pair models are revived (Zdziarski [15]). Indeed, the pair models discussed above saturate at an energy index of 0.9 to 1 in the case of very compact sources. The steepening effects of the pair cascade and of Thomson down-scattering by the cooled pairs (before they annihilate) is masked by the flat reflection hump.

SUMMARY

At the present time it looks as if electron-positron pairs are important in AGN. The simple pair models in which an accelerator injects relativistic electrons into the emission region, which also contains soft photons, perhaps from an accretion disc, appear to give good spectral agreement with the observations, provided that there is a also a reflected component. It means that the primary spectrum produced by the accelerated electrons is almost totally hidden by the radiation of pairs created in photon-photon collisions and by the reflected continuum. This is both good news and bad news; good because we may at last be understanding the origin of the continuum, bad because it tells us very little about the accelerator itself.

The accelerator must take electrons to Lorentz factors of 10^3 or higher very quickly. Much faster than the cooling time which is presumably much less than the observed variability time (at least $\ell\gamma$ times less), and so less than 50s in the case of NGC 6814. The effects of dead electrons are perhaps minimized if they are pairs and annihilate. Whether there is any feedback such as pair loading is not yet clear.

Perhaps we shall learn more about the operation of the central engine, rather than about radiation from a compact region, when the Gamma-Ray Observatory is operational and when we begin to understand the rapid variability common to the sources.

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