MODELS FOR THE X-RAY EMISSION FROM RADIO QUIET AGNs

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ABSTRACT. The current status of understanding of the X-ray emission from Seyfert galaxies involves thermal Comptonization of soft photons by mildrelativistic electrons and positrons. I review observational and theoretical arguments supporting such a view, discussing current models proposed for the structure of the innermost part of the accretion flow: extended coronae, small scale flaring blobs, advection dominated accretion disks and small scale cold cloudlets.

1. Introduction

One of the most remarkable aspect of AGNs is the strong X-ray emission, the origin of which may be directly related to the central engine powering the active galaxy. In fact the rapid X-ray variability detected in several sources (e.g. McHardy 1989); indicates that the X-ray production region is very close to the central object. The study of the mechanisms leading to such a strong X-ray emission is then extremely important in view of understanding the physical condition of the inner regions of AGNs. While in radio loud objects the bulk of the emission seems to be non thermal (e.g. Ghisellini & Madau 1996), in Seyfert galaxies there is evidence of the presence of cold thermal matter near the central engine (Pounds et al. 1990). The accreting supermassive black hole picture is widely accepted for unbeamed objects, and the strong UV excess is thought to be the signature of the accretion flow. In this picture the origin of the X-rays remains unclear, and any successful model needs to satisfy three main observational constrains:

1. the size of the X-ray production region must be small, few gravitational radii, as indicated by the fast variability (McHardy 1989);
2. the observed spectrum in the hard X-rays (2-20 keV) is close to a power law, with a small dispersion in the value of the spectral index, with mean value of \( \approx 0.7 \pm 0.15 \) for Seyfert galaxies (e.g. Mushotzky 1984). At higher energies the power law shows a break. Force fitting an exponential cut-off to the break, the e-folding energy is comprised between 50 and 300 keV (Madejski et al. 1995);
3. whatever produces the X-rays is close to cold reflecting matter, as inferred from the presence of fluorescent Fe line emission and Compton reflection hump peaked around 30 keV. After deconvolution of the latter component the spectral index of the underlying power law is revised to \( \approx 0.9 \) (Pounds et al. 1990).

Two classes of models have been proposed to explain the shape of the X-ray spectrum. One is based on the production of very high energy primaries and strong repro-
cessing via electromagnetic cascades leading to the formation of an $e^\pm$ pair plasma (e.g., Zdziarski et al. 1993). The second involves multiple Compton scattering (Comptonization) of soft photons on a thermal population of hot electrons (see Svensson 1996 for a recent review).

In this contribution I shall discuss some aspects of the origin of the X–rays in Seyfert galaxies. I will concentrate mainly on the radiation generation mechanisms. Then I will review some current pictures of the innermost part of the accretion flow in radio quiet AGNs. For a somewhat different approach the reader may be interested in reading the review by Maraschi & Haardt (1996).

2. Thermal or non Thermal X–rays?

The X–rays emitted by AGNs have obviously a non–thermal spectrum. The question addressed in the title above rather regards the particle distribution responsible for such an emission, which is largely unknown and that can well be thermal. Before speculating the nature of the particle distribution, it is important to ask (and possibly answer to): how do particles cool down?

Fast particles cool down by means of three possible interactions, namely particle–particle, particle–photon and particle–magnetic field, transforming kinetic energy into free–free (FF), inverse Compton (IC), and synchrotron (S) radiation, respectively. Which one dominates remains to be seen. The concept of ”compactness” $\ell$ is useful to assess the importance of different radiation mechanisms. The compactness is defined as

$$\ell \equiv \frac{\sigma_T L}{m_e c^3 R} \simeq 10^4 \frac{\mathcal{L}}{r}$$

where $L$ is the luminosity in Eddington units, $r$ is the source size in units of $2GM/c^2$, and the other symbols have their usual meaning.

Neglecting for the moment S emission, and assuming that the gas is thermal, the relative importance of FF vs. IC emission can be translated into a limit for $\ell$. One can easily find that if

$$\ell \gtrsim 0.03/\sqrt{kT_e/m_e c^2}$$

IC cooling is much faster than FF cooling. Now the value of the compactness in Seyfert galaxies is largely unknown, but rough estimates range from 1 to 300 (Done & Fabian 1989). This, together with the OSSE results indicating $kT_e \simeq 50 – 300$ keV, implies that IC cooling is largely dominant.

Another nice property of the compactness parameter is immediately evident once we notice that $\ell$ is proportional to the photon–photon opacity for pair production. For $\ell \gtrsim 60$ the hot gas cools down via radiation emission and via mass $(e^+e^-)$ production. From the observed values of $\ell$, we argue that $e^+e^-$–pairs are an important ingredient of the X–ray emitting gas in Seyfert galaxies.

The role of S cooling, neglected so far, depends on the basically unknown value of the magnetic field. Taking an equipartition field, the primary S emission is, under the expected conditions, almost completely self–absorbed. In other words, synchrotron photons may play a role as a soft input for Comptonization (SSC models, see next), rather than being directly responsible for the cooling.
Now I will try to justify the assumption that the gas is thermal.

The main difference between thermal and non–thermal models consists in the assumption made on the channelling of the available power. If the power is equally channeled into all the electrons we talk about thermal plasma, while if the power is channeled into a tiny fraction of the electrons we are dealing with non–thermal plasma. Physically, one can think that in a thermal plasma the cooling time is longer than the particle–particle collision time, the contrary for a non–thermal plasmas.

In the thermal Comptonization models (e.g. Sunyaev & Titarchuk 1980), the underlying assumption is that all the emitting particles are heated and maintained in a Maxwellian distribution at constant temperature, despite the rapid variations in luminosity that are observed. Density and temperature of the electrons were usually assigned in a rather ad hoc way, in order to produce a power law spectrum with the observed index, but this problem has been solved considering the interplay between the cold accretion disk, and the hot corona (Haardt & Maraschi 1991, 1993; see also next §3).

Non–thermal pair models (for a review see Svensson 1992, 1994) predict the correct spectral index with the only assumption that $\ell > \sim 60$, and then, for this reason, they seemed to be favoured. On the other hand, after the OSSE results was clear that the steepening of the hard X-ray spectrum above 100 keV predicted by non–thermal models was only barely as sharp as the data required (e.g. Maisack et al. 1993). Furthermore, the non–thermal pair model predicts a flattening of the spectrum at $\sim 100 – 200$ keV, and the presence of a conspicuous annihilation line, neither of which is observed. OSSE observations instead can be interpreted in the framework of thermal Comptonization models. If this is the case, also the X–ray background can be best explained as the sum of the emission of Seyfert galaxies (see e.g. Madau et al. 1993, 1994).

Finally I would like to recall that the observed rapid X–ray variability was longer considered as an evidence against thermal models. However Ghisellini et al. (1993) demonstrated that in the spectrum formation what really matters is the average energy of the particles rather than the shape of the particle distribution. No matter what the shape is, as long as the average particle energy is small (as result of, e.g., pair cascade with particle re–acceleration), the emitted IC spectrum is practically indistinguishable from that emerging from a thermal particle distribution.

However the particle distribution could be genuinely thermal. Ghisellini et al. (1996) show that relativistic electrons (and positrons) can thermalize in few synchrotron cooling times by emitting and absorbing cyclo–synchrotron photons. Such a mechanism is enormously faster than Coulomb interactions, overcoming any problem related to fast variability.

3. Modeling the Inner Region

Once argued that thermal IC is the main radiation mechanism at high energies in Seyfert galaxies, the next question arising is: what is the relation of the X–ray source to the cold matter responsible for the UV emission? Here I briefly review four models proposed in the last years for the innermost part of AGNs. The cartoon version of these models is sketched in Fig.1.
3.1. Extended Coronae

In Haardt & Maraschi (1991, 1993) we developed a model based on thermal Comptonization. The hot electrons are thought to be located immediately above the cold reflecting matter so that the soft blackbody photons emitted by the cold layer provide the main source of cooling for the hot electrons. At the same time the hard photons produced by Compton scattering in the hot corona are an important source of heating for the underlying cold layer which reprocesses them into soft photons. This interplay between the two phases is the basic feature of the model.

We found that the observed spectral features could be explained if the hard-to-soft luminosity ratio within the corona is $\sim 2$. In fact such a value implies a Compton parameter close to 1, that in turn leads to a power law index close to 1. This value is naturally obtained if one assumes an extended corona where the whole gravitational power is released, the cold disk working as a mere reprocessor. For any value of the electron density of the corona, the temperature adjusts to maintain the same luminosity ratio and so the same spectral index in the emitted spectrum.

The optical depth of the corona is in turn fixed by the compactness parameter, and
the resulting equilibrium temperature is tantalizingly close to the derived value from OSSE data (e.g. Madejski et al. 1995).

3.2. Flares above the Disk

The crucial assumption in the extended corona model above is that all the available gravitational power is dissipated in the hot corona, the cold accretion disk acting as a mere reprocessing and reflecting layer. Though this idea gained recently theoretical support (see Balbus et al. 1996), we may wish to lose this tight constrain. This can be done considering small scale flaring regions above the surface of the accretion disk rather than a smooth extended corona.

The basic idea is that the disk magnetic field can drain part of the accretion power outside the accreting flow. In the picture described by Galeev et al. (1979), the disk differential rotation causes the azimuthal magnetic field to grow exponentially, if a feedback mechanism operates in order to link the radial component of magnetic field \( B \) to the azimuthal one, \( B_\phi \). The authors showed that disk convection could be a reliable way to do the job. In general, the growth of \( B_\phi \) stops when non linear effects become important, or because of reconnection of the field lines. The latter mechanism is unlikely to be effective within the disk, and it can be shown that the magnetic field can reach the pressure equilibrium with the surrounding gas, with a subsequent buoyancy of the magnetic flux tubes. In the much more rarefied coronal ambient magnetic reconnection occurs rapidly because of the increased Alfven velocity, so that the stored magnetic energy can be transferred to particles, that in turn radiate.

The emitted spectrum from the active blobs depend on the dominant energy loss mechanism effective in cooling the hot particles. One should compare the energy losses due to bremsstrahlung, cyclotron, synchrotron, inverse Compton radiation and thermal conduction to the lower cold gas, finding in which regimes IC dominates. In Haardt et al. (1994) we showed that the conditions of single blobs are the same as the extended corona (and hence match observations) provided that the time needed to transfer the accumulated magnetic energy to the particles is much shorter than the dynamo time scale.

The cooling of the blob plasma is provided by the reprocessed soft photon flux below the blobs. The temperature of the reprocessed radiation can be much higher than that due to the inner disk dissipation, so that the temperature of the thermal radiation below the blobs will be in general higher than the temperature of the disk emission at the same radius, producing a hotter thermal component superimposed to the multicolor disk emission. In this frame the seed photons for Comptonization in the blobs should be related to the observed EUV–Soft X–ray excesses rather than to the UV bump. Long term variability can be ascribed to variations of the accretion rate, while short term variability can be due to stochastic noise in the number of flaring blobs, that do not need to be related to the accretion rate.
3.3. Advection Dominated Accretion Disks

The new class of so-called Advection Dominated (accretion) Disks (ADDs) has been proposed to explain the X-ray emission from underluminous AGNs (e.g. Chen et al. 1995, and references therein), though with a somewhat extreme choice of parameters the model could be relevant for "normal" Seyfert galaxies as well (Narayan & Yi 1995).

In ADDs the basic underlying idea is that Coulomb collisions are not fast enough to transfer energy from ions (supposed to be directly energized by the accretion process) to electrons. Ions require a catalyzer (the electrons) to produce photons and hence to cool down. If the interaction between the two species is slow, ions "advect in" part of the energy gained as they fall into the hole. This happens if the density of the accreting material is low, i.e. at low accretion rates. Note that on the other extreme, i.e. at very high accretion rates, the density can be so high that photons are trapped into the flow. Also in this case, but for completely different reasons, advection sets in. The gas is however cold, and not interesting in the context of X-ray emission.

On the low accretion rate branch, the whole process can be best understood in terms of timescales. The three competing timescales are the viscous timescale $t_{\text{visc}}$, the Coulomb timescale $t_{p-e}$ and the cooling timescale for electrons $t_{\text{cool}}$. Viscous processes provide the heating term for ions, while Coulomb collisions are at the same time the heating term for electrons and the cooling term for ions. While ions are heated at a constant rate (given the input disk parameters), electron heating and ion and electron cooling rates are proportional to the energy content of the gas. Under typical conditions, in the inner part of the flow we have

$$t_{\text{cool}} \ll t_{\text{visc}} \ll t_{p-e} \quad (3)$$

The above relations immediately show that a) energy is advected in by protons (or more generally ions), and b) the plasma is at two temperatures, with $T_e < T_p < (m_p/m_e)T_e$. Once heated, electrons cool down very rapidly.

The main result of the conditions described above is that in ADDs the accreting flow is itself extremely hot, with temperatures of few hundreds keV, and hence it is directly responsible for the X-ray emission. We may say that the disk plays the role of the extended corona, with the main difference that in ADDs there is no cold matter whatsoever (at least in the innermost regions). The hot disk cools through IC losses. The soft photons to be Comptonized are provided by internal S and FF emission, rather than by an external soft photon input as in the extended corona model. S emission, though mostly self-absorbed, is probably more intense than FF. From the point of view of radiation mechanisms, we may say that ADDs are then SSC thermal models. We finally note that in ADDs there are no apparent reasons leading the Compton parameter to be constant close to 1, so this class of models may have difficulties in explaining the small dispersion of the [2-20] keV spectral index distribution observed in Seyfert I galaxies (Nandra & Pounds 1994). Also the reflection component and the iron line at 6.4 keV are not well explained.
3.4. EUV Cloudlets

The three models described so far assume that the accreting matter is in an accretion disk fashion (though in ADDs it turns out to be geometrically thick). In the first two examples the X–rays are produced in a hot atmosphere (extended or localized) located above the cold gas, while in ADDs the disk itself is so hot to become the X–ray source.

A radically different view was originally proposed by Celotti et al. (1992), and studied in details by Kuncic et al. (1996). The hot X–ray atmosphere is supposed to be extended, but unlike ADDs, it is filled with small cold clouds responsible for the EUV thermal emission, possibly providing soft photons for IC emission in the hot phase.

In the cloudlet model, the size of the clouds, which are probably confined by magnetic fields, can be as small as few meters. These small cloudlets are supposed to be Thomson thin, heated by FF absorption, and cooled via collisionally–excited line radiation and FF emission, which process dominates depending on temperature and density. The cloudlets can account for only part of the observed UV bump, as they emit the bulk of radiation in EUV lines and continuum. The authors argue that the spectral energy distribution of radio quiet AGNs may indeed reach a maximum in the EUV band, rather than in the optical–UV (for a criticism to this point see Haardt & Madau 1996).

In the model version proposed by Collin–Souffrin et al. (1996), the clouds are supposed to be Thomson thick. In this case the main source of radiation is free–bound emission, and, depending on the cloudlet filling factor, the emission can potentially account for the whole UV bump.

Both the groups focused their studies on the thermal emission from the clouds, rather than on the X–rays produced in the hot medium. On the framework of combined UV-to-X ray emission, the interplay between the hot gas and the cold cloudlets needs to be studied in detail.

4. Conclusions

In the previous sections I have schematically reviewed some aspects of the problems relative to the X–ray emission from Seyfert galaxies. After giving evidences of the thermal nature of the IC emission from this class of sources, I described four current models for the inner region.

With the present state of the models, and on the basis of currently available observations, it is difficult to favour one model with respect to the others. In principle discriminating observations could come from timing properties of X–ray light curves, comparing properties as time–lags, power spectra and coherence in different X–ray bands (see e.g. Vaughan & Nowak 1996). As a matter of fact most of the information at high energies is expected to come from observations of Galactic black hole candidates (GBHCs). In this perspective, models tailored to fit the larger size of AGNs will possibly arise from interpretation of Galactic data.

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