Constraints on Central Engine Models from Rapid X-ray Variability

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ABSTRACT:

We discuss the implications of recently published GINGA and EXOSAT data on rapid X-ray variability in AGN. We conclude that the observed behavior of the iron Kα fluorescence line cannot be explained by the reprocessing of hard X-rays by a standard accretion disk, unless most of the X-ray luminosity is generated in local regions close to the disk, with a size smaller than R_g. Observed power density spectra of X-ray variability can be reasonably well modelled with a reservoir mechanism. (Based on transcript of talk delivered by M. Begelman.)

1. INTRODUCTION

New X-ray data from GINGA and EXOSAT may be telling us some important things about the processes that go on close to the central parts of AGN. A number of very rapidly variable X-ray continua have been observed recently. The variable flux includes the hard continuum above a few kilovolts, and some of the soft X-ray excesses at a fraction of a keV up to a keV have also been observed to be rapidly variable (Turner and Pounds 1988; Pounds, this volume). To my knowledge, the record-holder for variability is the Seyfert galaxy NGC 6814, which has been observed to change its apparent luminosity by about 10^{43} erg s^{-1} in 50 seconds (Kunieda *et al.* 1990). The observed change was a substantial fraction (about half) of the apparent luminosity at that time. Perhaps even more remarkable is the spectral evidence that a significant fraction of the hard X-rays is being reprocessed by relatively cold gas, some of which is located in the same compact region. In particular, many sources show a Kα line from relatively neutral iron (meaning that the K-shell seems to be quite complete), which has such a large equivalent width that it is almost certainly due to fluorescence in a situation where the cold gas is intercepting a large fraction of the very hard X-ray flux (Nandra *et al.* 1989; Pounds *et al.* 1989, 1990). Amazingly, the Fe Kα fluorescence in NGC 6814 seems to vary more or less in phase with the 2–20 keV flux (with a time delay of less than 250 seconds), indicating that this reprocessing is occurring very locally (Kunieda *et al.* 1990). The observational results to which I refer will be discussed in greater detail by Jane Turner and Ken Pounds later this week. I will devote the better part of this talk to some of the theoretical inferences one can draw from these observations.

2. THERMAL STATE OF GAS IN THE CENTRAL ENGINE

These observations are probably the strongest evidence to date that there really is cold gas in the central engine. It is not too surprising to find cold gas in the central engine, because optically thick gas will tend to reprocess the ambient radiation (energy density U) and equilibrate to the effective black body temperature $T_{bb} = (U/a)^{1/4}$. In terms of the parameters which appear to be typical of NGC 6814:

$$T_{bb} > \left(\frac{\Delta L}{4\pi a c^3 \Delta t^2}\right)^{\frac{1}{4}} \sim 2 \times 10^5 \left(\frac{\Delta L_{43}}{\Delta t_{50}^2}\right)^{\frac{1}{4}} \text{ K},$$

where $\Delta L_{43} \equiv \Delta L/10^{43}$ erg s^{-1} is the luminosity produced in the varying region and $\Delta t_{50} \equiv \Delta t/50$ sec is the variability timescale. When I talk about the varying regions, I am not assuming at this point that the whole "central engine" of the AGN is varying. I think that this is still an open question, to which I will return later. The cold gas intercepts an amount of hard X-rays similar to the observed luminosity, so it must cover a large part of the sky if viewed from the source of the hard X-ray flux. To explain the fluorescence line, the cold gas must also absorb most of the incident flux at energies just above the iron K-edge. This implies that the optical depth of the cold gas to electron scattering cannot be very much smaller than one.

The rapid variability indicates that the "compactness" ℓ of the varying regions is high,

$$\ell > \frac{\Delta L \sigma_T}{4\pi m_e c^4 \Delta t} \sim 14 \frac{\Delta L_{43}}{\Delta t_{50}} > 1.$$

I will not discuss the possible implications of a large compactness for pair production models or for specific radiation mechanisms. What I wish to point out is that this implies that any electrons that are hotter than the inverse Compton temperature, i.e., relativistic electrons and hot thermal electrons of T greater than 10^7 K or 10^8 K, will cool down to the inverse Compton temperature T_{IC} on a time scale that is short compared to the light crossing time across the varying region ($t_{cool} \sim \Delta R/c\ell$). Consequently, it is unlikely that a large fraction of the energy in these objects at any one time resides in relativistic or hot thermal electrons. Any energy that is put into hot or relativistic electrons would be rapidly transferred to radiation, and lost (unless the radiation is trapped by a large optical depth). In a highly variable source, the distribution of hot electrons is likely to be time dependent and inhomogeneous on small scales.

In order to remain cold despite X-ray heating, the irradiated gas must be sufficiently dense. The thermal state of X-ray irradiated gas in an AGN has been studied recently by Guilbert and Rees (1988) and Ferland and Rees (1988). Since the observed hard X-ray spectrum is not very steep, the inverse Compton temperature associated with the hard X-rays is probably of order 10^8 K. When combined with the soft radiation that is probably present (e.g., reprocessed X-rays and primary UV radiation from an accretion disk), it is probably still larger than 10^7 K because a significant fraction of the flux is in hard X-rays. Gas exposed to that kind of spectrum tends to have a bimodal behavior. If it is dense enough, it will be able to process the radiation and equilibrate at a temperature close to T_{bb} ($\sim 2 \times 10^5$ K). But if it is not dense enough, the two-body interactions between particles needed to cool the gas will not be able to counteract the heating effect of the X-rays and the gas will tend to heat up to the inverse Compton temperature.

It turns out that the transition between these two temperatures occurs rather suddenly. Ferland and Rees plotted temperature versus density, which gives a very smooth transition, but this is a bit misleading. If you instead plot temperature versus pressure of the gas, or versus radiation pressure divided by gas pressure, which is sometimes called the ionization parameter, the transition is very steep, and may even "double back" (Fig. 1). Thus, there will be a tendency for most

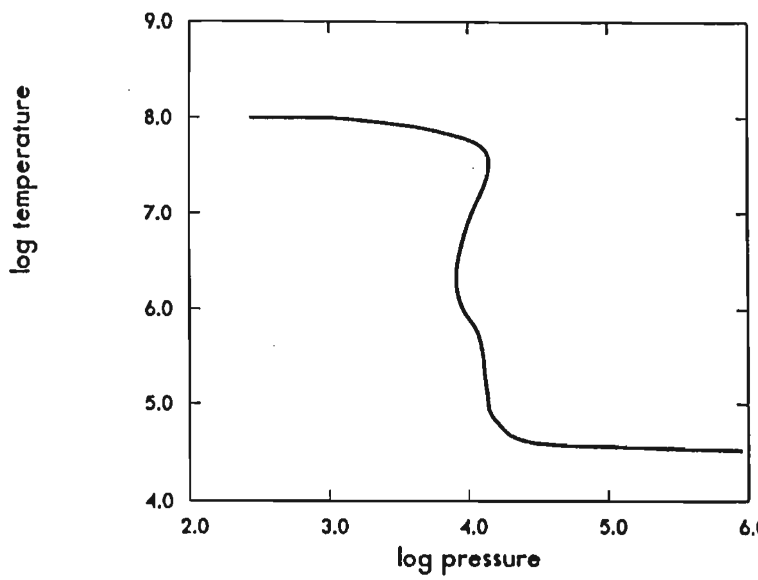

Fig. 1. The equilibrium temperature as a function of gas pressure for an optically thin gas irradiated by a spectrum $F_\nu \propto \nu^{-0.7}$, with a total flux appropriate to the central regions of an AGN (after Ferland and Rees 1988).

of the gas either to be close to T_{bb} or to heat up to T_{IC}, with very little gas at intervening temperatures. If the p vs. T curve doubles back, then gas at intervening temperatures is thermally unstable, and there is a range of pressures over which the hot and cold phases can coexist at fixed pressure (Krolik, McKee and Tarter 1981). The exact conditions under which the phase transition occurs are not very sensitive to the spectrum of the radiation, and correspond to a situation where the radiation pressure and the gas pressure are comparable. Thus, if the radiation pressure is larger than the gas pressure by a significant amount then the gas will be heated up to the inverse Compton temperature. Conversely, the density required to keep the gas down at the cold temperature is approximately

$$n > 10^{16} \left(\frac{T_{bb}}{10^5 K}\right)^3 \quad \text{cm}^{-3} \quad .$$

What is the distribution and dynamical state of the cold gas in an AGN? Some dynamical support is necessary, because 10^5 K is orders of magnitude below the virial temperature in the central engine. One possibility is that the gas is supported by angular momentum, in which case the most likely geometric configuration would be a disk. Confinement is then by the vertical component of gravity. Alternatively, as Guilbert and Rees (1988) have suggested, the gas might be in the form of filaments which are both confined and prevented from settling into a thin disk by very powerful magnetic fields (Rees 1987). It is unlikely that the cold gas could be confined by the pressure of a hot intercloud medium in thermal equilibrium, since T_{IC} is also well below the virial temperature. Gas at $10^7 - 10^8$ K may contribute significantly to confinement in the broad or narrow emission line regions, but not in the innermost regions of the nucleus. Any significant contribution to gas pressure confinement would presumably have to have to come from a "two-temperature" plasma (Rees *et al.* 1982), with most of the pressure being provided by ions.

3. IMPLICATIONS FOR ACCRETION DISK MODELS

Could the the cold gas responsible for reprocessing the X-rays comprise the inner part of the much sought-after accretion disk? If we assume that the very short time scale variability in NGC 6814 reflects global fluctuations of the inner parts of the accretion disk, we can infer that the observed luminosity is at least a tenth of the Eddington limit (Kunieda *et al.* 1990). The inner parts of the disk would be supported by radiation pressure. This is not auspicious for maintaining a cold reprocessing layer on the surface of the disk, because it means that the radiation pressure in the surface layers of the disk, as well as everywhere in the interior, has to be much greater than the gas pressure. Roughly,

$$\frac{P_{rad}}{P_{gas}} \sim 10^4 \left(\frac{L}{L_{Edd}}\right)^2$$

at the photosphere. Recall that, in order for gas exposed to hard X-rays to remain cold, the gas pressure has to be comparable to or larger than the radiation pressure; here, the ratio of radiation pressure to gas pressure is greater than 100.

Thus, if our lower bound on L/L_{Edd} is correct, then we expect the irradiated surface layers of the disk to heat up to the inverse Compton temperature (or higher, if there are other local sources of heating such as magnetic reconnection). At such temperatures the iron K-shell will be largely stripped, hence the gas will not produce the observed fluorescence line when irradiated by hard X-rays. Given that the disk is clad by an X-ray heated corona, what are the prospects for passing the hard X-rays through the corona to induce fluorescence in the layers below? To obtain a significant fluorescence yield requires a region in which iron is in a sufficiently low ionization stage *and* hard X-ray photons are present. To avoid too high an ionization state due to collisional ionization the gas temperature has to be below $\sim 3 \times 10^6$ K. If the radiation pressure in ionizing photons is significantly larger than the gas pressure photoionization is likely to be more important than collisional ionization, and the requirement is that the "color temperature" T_X of the hard radiation field has to be less than $(4-8) \times 10^6$ K. How deep does one have to go into the disk before these conditions are met? First we note that if the X-ray luminosity of the object is comparable to the blackbody luminosity, as seems to be observed, the radiation pressure in hard, ionizing photons is much higher than the gas pressure, and hence both the gas temperature and T_X have to be below a few times 10^6K. The gas temperature will be equal to the Compton temperature of the total radiation field:

$$T_{gas} = T_{IC} \sim \frac{J_{bb}T_{bb} + J_X T_X}{J_{bb} + J_X}$$

where J is the average intensity and the subscript bb refers to thermal radiation from inside the disk. From a simple gray atmosphere model we know that J_{bb} increases linearly with optical depth, whereas J_X in first approximation remains constant or decreases with optical depth. Thus, the inverse Compton and gas temperatures decrease at least as fast as τ^{-1}, and will become less than a few times 10^6K at an optical depth of order 10 or less. The hard photons diffusing into the disk will lose energy by Compton downscattering. Assuming that the layer is cold ($T_{gas} \ll T_X$), a photon of energy kT_X will be strongly downscattered where the optical depth satisfies the condition

$$\frac{4kT_X}{m_e c^2}\tau^2 = 1.$$

Thus, photons with an initial energy above $(4-8)10^6$ K will have lost their excess energy at optical depths greater than $(14-20)$ and there will be a cutoff in the spectrum. This constraint turns out to be more restrictive than the one on the gas temperature, since the ionization state of iron is more sensitive to the color temperature of the hard radiation than to the kinetic temperature of the gas.

This result does not bode well for producing the iron fluorescence line in the sub-coronal layers of the disk, because when you get down to depth where the K-shell recombines, nearly all of the photons that are capable of causing fluorescence have been downscattered below the K-edge. A very crude estimate (assuming that the hard photon distribution evolves into a Wien spectrum) suggests that only a fraction of order $10^{-3}-10^{-5}$ of the incident X-ray photons will be available to cause fluorescence at these depths. Furthermore, if any Kα photons were produced, they would be downscattered before they escaped and would not be observed as line photons. However, this type of X-ray heated corona may play a role in explaining some other aspects of AGN spectra. Many of these sources seem to have a significant soft excess in X-rays at energies which are somewhat larger than what you would expect from the thermal radiation of the accretion disk. Comptonization by the corona could be significant, especially if some of the energy released in the disk goes directly into heating, and could lead to an enhancement of the soft X-ray flux.

To review what I think are some of the problems or uncertainties in applying the standard accretion disk model in the light of recent X-ray observations: If the luminosity of the disk is greater than a small fraction (~ 0.03) of the Eddington limit, it seems hard for reprocessing by the disk to produce the observed Kα fluorescence line locally so that it can vary in phase with the hard X-rays, because the irradiated layers are too hot and optically thick. The assumption that the luminosity is close to the Eddington limit comes from assuming that the entire inner region of the disk is varying. If you drop that assumption, and assume instead that the disk is very much less luminous than the Eddington limit, then the Kα fluorescence line could be produced locally in the surface layers of a thin accretion disk. In this case the observed rapid variability would not result from global fluctuations of the disk, but might be associated with flares or flashes occurring over a very much smaller scale.

4. ALTERNATIVES TO ACCRETION DISKS

Another possibility is that the standard accretion disk theory does not apply in the central regions of AGN. A thermal component in the spectrum, with roughly the right temperature for an accretion disk, does not necessarily mean that a disk is present. It simply means that there is probably some optically thick gas, which is able to thermalize and reradiate whatever radiation is present. Even if the gas in the center of these sources forms a disk, it may have a structure very different from that of a standard α disk. If we demand that the gas pressure be comparable to or larger than the radiation pressure in order to produce the fluorescence line, then we will be seeking a model in which the energy released by accretion is not dissipated into radiation inside the cold gas itself. In this limit the cold gas will be isothermal, at a temperature close to the local black body temperature.

A disk which is supported by gas pressure and confined by the vertical component of the central black hole's gravity would be very thin compared to a standard radiation pressure-dominated accretion disk. Its density would have to be larger than about 10^{16}cm^{-3} in order to stay cool, but a much higher density inside the disk is guaranteed anyway if the primary energy source is disk accretion. How could a disk provide this luminosity without becoming radiation pressure supported? To construct a model with this property, we would have to drop one of our most cherished assumptions about accretion disks, namely that the energy that is released by gravitational infall is dissipated inside the disk and radiated. The energy is presumably stored in some other form, perhaps in twisted loops of magnetic fields which ultimately pop out of the disk, reconnect, and release the energy in the form of heat. Comptonization of soft photons in these heated regions then produces X-rays and gamma rays, generating a hard flux that shines back down on the disk and is reprocessed. In other words, the dissipation of the gravitational binding energy is occurring externally. The advantage of having a disk reprocess the hard flux is that it automatically has a large optical depth and a large covering factor, so it is easy to get the required equivalent width of the iron fluorescence line as well as the other signatures of X-ray reflection that we will hear about later this week. An interesting feature of this kind of model is that there is no Eddington limit on the energy output of such a disk, because the radiation is shining down on the disk from the outside.

Alternatively, there need not be a disk at all. Rees and collaborators (e.g., Guilbert and Rees 1988) have proposed that the cold gas forms a chaotic array of filaments which are flying around. It is likely that if a configuration like this existed it would have to be confined and supported by the energy density of very strong magnetic fields, since confinement by the thermal pressure of hot gas is difficult so close to the central black hole (see above). Confinement of individual filaments would require a magnetic energy density of at least 10^5 erg cm^{-3}, comparable to the local radiation energy density. Dynamical support against gravity would demand a magnetic energy density at least as large as the mean kinetic energy density contained in the motion of the filaments under the influence of gravity. In order for the same magnetic field strength to both confine and dynamically support the filaments, the filling factor of filaments must be quite small, of order $T_{bb}/T_{vir} \sim 10^{-5}$, where T_{vir} is the local virial temperature. To produce the observed Kα fluorescence line, this model would have to satisfy a couple of additional constraints, i.e, the filaments would have to intercept a large fraction of the hard X-ray flux and they would have to have a significant optical depth to Thomson scattering. Will these constraints be satisfied "naturally," or do they require "fine-tuning?" I don't have an answer at present.

Our search for possible alternatives to a standard accretion disk model has been motivated by the hypothesis that the observed rapid and large amplitude X-ray variability represents a global fluctuation of the central engine. Yet there is no compelling evidence that this is the case. In fact, the are no strong indications that the minimum values of Δt observed to date reflect any characteristic scale of the central engine. When we observe with higher time resolution, we may well detect even faster variability! This suggests that we should also consider models in which the variability is localized. Since the amplitude of variability is so high, the energy of a fluctuation probably has to be stored up in a small region, and released in a very intense form on a short time scale. If local flaring were the cause of variability, then we could say little about L/L_{Edd} or the mass of the black hole. Flare energy could be stored, for example, in intense magnetic flux tubes or in the kinetic energy of filaments.

In flaring models which involve thermal emission processes, optical depth effects may significantly constrain variability. For instance, models in which the kinetic energy of filaments is dissipated in filament–filament collisions are limited to producing fluctuations with $\Delta L/\Delta t < m_p c v^3/\sigma_T \sim 10^{42}(v/c)^3$ erg s^{-2}, where v is the relative velocity of the filaments. Observations are now pushing $\Delta L/\Delta t$ up into the range of 10^{38} to 10^{42} in some sources, implying that the filament velocities would have to exceed 0.1c if this type of model applies. Furthermore, existing observations are already pushing one popular emission mechanism, self-Comptonized bremsstrahlung, close to the precipice. As Zdziarski (1986) pointed out, the upper limit to $\Delta L/\Delta t$ for a Comptonized bremsstrahlung source is given by

$$\left(\frac{\Delta L}{\Delta t}\right) < 10^{38}\left(\frac{R_g}{R}\right)^{\frac{1}{2}}\tau[\ln(2.5/x_{min})]^2 \text{ erg s}^{-2},$$

where x_{min} is the low-frequency cutoff energy in units of $m_e c^2$. Because bremsstrahlung is such an inefficient mechanism, a high radiation flux requires a large column density and hence a large optical depth, which in turn limits the rapidity with which the source can vary.

5. X-RAY POWER DENSITY SPECTRA

There appears to be some tendency for the power density spectra (PDS) of X-ray variability in Seyferts to be fairly featureless power laws with slopes often steeper than f^{-1} but flatter than f^{-2} (where f is the frequency of the Fourier component) (Lehto, McHardy, and Abraham, this volume). What might this be telling us about the processes that are causing the variability? A pure Poisson process, with a fixed rate constant, gives white noise, i.e., the power density spectrum is flat. The other famous noise spectrum that one finds and understands is produced by integrating the fluctuations of white noise in time, giving a PDS proportional to f^{-2}. If we assume that the underlying fluctuations are random (Poisson) then to obtain the observed PDS there must be some kind of "filter" which introduces enough excess power at low frequencies —i.e., long term correlations — to steepen a fairly flat PDS by more than one power of f.

It is easy to find mathematical ways of achieving this. In fact, the problem is that there are too many mathematical ways of doing it, and it is very difficult to pick out physical features which motivate any particular one. This partly reflects the fact that the PDS is a very crude statistic — two noise trains may have identical PDS yet look completely different to the eye. Press (1978) emphasizes this point in his article discussing the ubiquity and lack of understanding of $1/f$ noise. He shows that one way in which a Poisson process can produce $1/f$ noise is to have a pulse shape with a very slow decay, particularly with a decay going $\propto (t - t_0)^{-1/2}$. However, signals simulated according to this prescription that exhibit f^{-1} behavior over a significant frequency range do not resemble actual AGN X-ray data, in the sense that they have to have very large and narrow peaks to get sufficient power at short timescales. Also, I don't see any particular physical motivation to assume that this type of behavior occurs in AGNs.

A second way to filter a Poisson process to obtain a steeper power-law is to superpose white noise spectra with a range of normalizations and high-frequency cutoffs. One might imagine, for example, that the low frequency variations are introduced by slow fluctuations that occur in the accretion flow at large distances (and propagate into the center) and that higher frequency variations are introduced into the PDS at smaller distances. If we superpose those power density spectra, the envelope may look like a power law. Models in this category have been discussed by Abramowicz and collaborators and by Krolik.

A third modification is to assume that there are correlations between the pulse height and either the decay time of the pulse or the mean rate of pulses. Obviously, if the characteristic decay time of a flare increased with the energy of the flare, then this would enhance the low-frequency end of the PDS. Physically, this might occur if the larger energy releasing regions are more luminous, causing larger flares to last longer. Correlations between pulse height and pulse rate might result from a "reservoir effect." A very large flare would drain the system of a larger amount of stored energy, with the result that it would take longer to store up enough energy for another flare. This is similar to what is thought to occur in one type of X-ray bursters.

We generated some artificial AGN variability using a reservoir model (Figs. 2, 3). We took burst amplitudes from an even distribution on some interval, then set the average time delay in the Poisson process in proportion to the amplitude of the last flare and let it go as a random process. Thus we have a modified Poisson process in which one of the parameters which is usually fixed depends instead on a random variable. In the first case, we kept the decay time fixed. The noise signal and its power density spectrum are given in Fig. 2. The power density spectrum we obtain is very close to f^{-1} noise over a couple of orders of magnitude in frequency. The frequency at the lower end of the power law is much lower than the characteristic frequency of pulses in our sample, showing that this kind of prescription leads to correlations which build up over many pulses. We also constructed a model in which we took the pulse decay time to be proportional to the burst amplitude and the delay time proportional to the energy in the last flare, i.e., to the amplitude squared (Fig. 3). There is much more low frequency power here, and the PDS is close to f^{-1} at high frequencies but steepens to f^{-2} at low frequencies. I leave it to the viewer to decide whether our synthetic light curves resemble the light curves of real AGN (see, e.g., Pounds and McHardy 1988).

6. SUMMARY

The interpretation of rapid X-ray variability in AGN is still far from clear. Inferences about the nature of the varying regions depend very strongly on assumptions about the structure of the source. If we believe that the observed fluctuations are global, then the central engines are fairly luminous compared to the Eddington limit. In this case it is difficult to see how a standard accretion disk could be responsible for producing the variable iron Kα flux by fluorescence, because the density of the disk's surface layers would be so low that they would heat up to

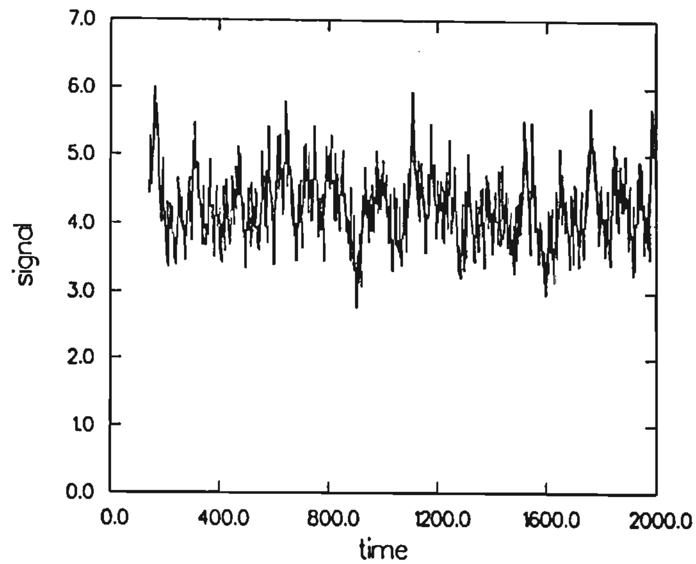

Fig. 2a. Simulated X-ray light curve generated by a reservoir mechanism, in which the average waiting time from one flare to the next is proportional to the amplitude of the last flare. The decay time of the individual flares is fixed at 20 time units.

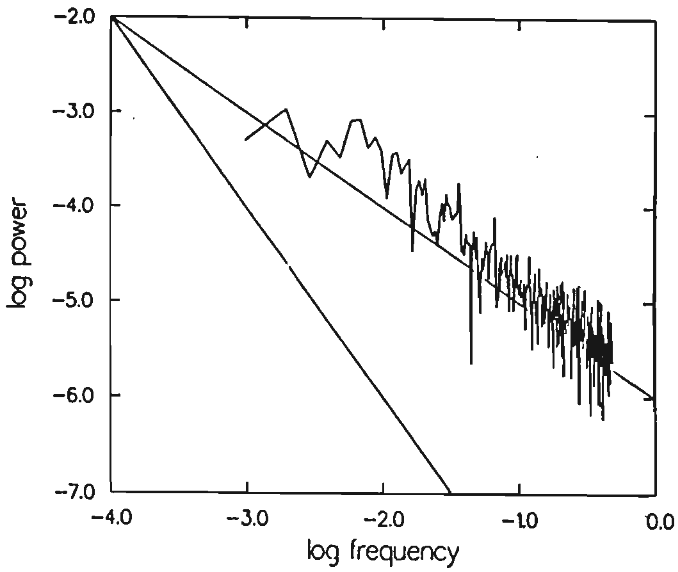

Fig. 2b. The power density spectrum of the time series illustrated in Fig. 2a. The straight lines represent f^{-1} and f^{-2} spectra.

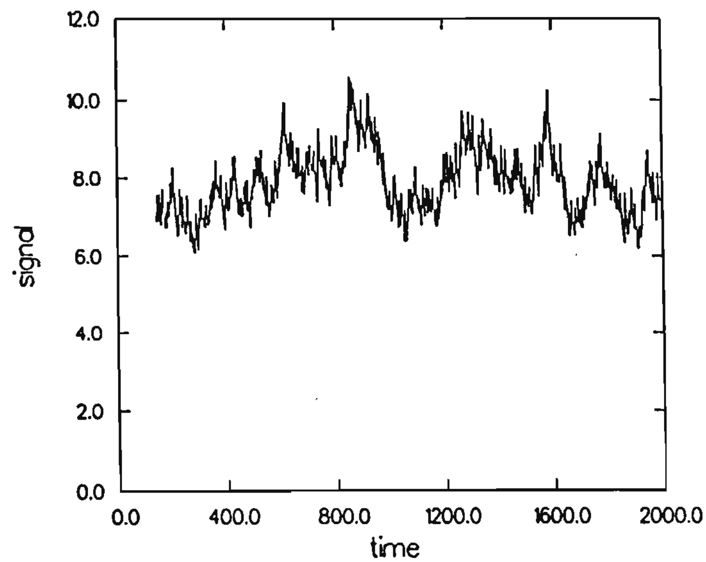

Fig. 3a. Same as Fig. 2a, but now the decay time of each flare is taken to be proportional to the amplitude, and the delay time is proportional to the energy contained in the last flare.

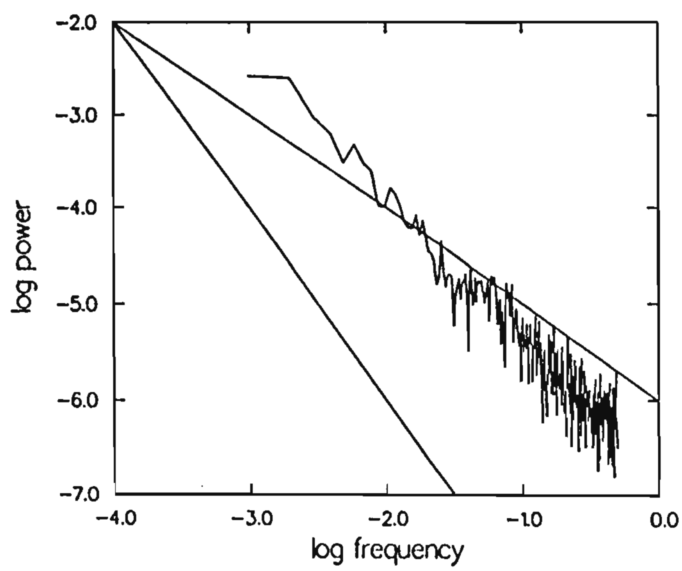

Fig. 3b. The power density spectrum of the time series illustrated in Fig. 3a.

the inverse Compton temperature. To explain the Kα flux by reprocessing requires denser gas, which is presumably not producing radiation internally. Denser gas also seems to be required to explain the absence of Lyman edges in QSO spectra (Ferland and Rees 1988; Czerny and Pojmański 1990). I suggested a couple of forms that this gas might take. I tried to emphasize that the observed short variability timescales may actually correspond to local rather than global variations in the central source; we have to try to collect information which would help us to distinguish between these two possibilities. For example, we should look on longer timescales to see if there is a feature in the power density spectrum, as I know that some people at this meeting have already been doing. Finally, I suggested yet another possible origin for the power density spectrum, which involves a reservoir effect or a correlation between the amplitude and the length of the flares.

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References

Czerny, B. and Pojmański G. 1990 MNRAS, 245, 1P

Ferland, G. J. and Rees, M. J. 1988, ApJ, 332, 141

Guilbert, P. W. and Rees, M. J. 1988, MNRAS, 233, 475

Krolik, J. H., McKee, C. F. and Tarter C. B. 1981, ApJ, 249, 422

Kunieda, H., Turner, T. J., Awaki, H., Koyama, K., Mushotzky, R., and Tsusaka, Y. 1990, Nature, 345, 786

Nandra, K. A., Pounds, K. A., Stewart, G. C., Fabian, A. C. and Rees, M. J. 1989, MNRAS, 236, 39P

Pounds, K. A. and McHardy, I. M. 1988, in Physics of Neutron Stars and Black Holes, ed. Y. Tanaka, Tokyo

Pounds, K. A., Nandra, K. A., Stewart, G. C., George, I. M. and Fabian, A. C. 1990, Nature, in press.

Pounds, K. A., Nandra, K. A., Stewart, G. C., and Leighly, K. 1989, MNRAS, 240, 769

Press, W. H. 1978, Comm. Ap. 7, 103

Rees, M. J. 1987, MNRAS, 228, 47P

Rees, M. J., Begelman, M. C., Blandford, R. D. and Phinney, E. S. 1982, Nature, 295, 17

Turner, T. J. and Pounds, K. A. 1988, MNRAS, 232, 463

Zdziarski, A. A. 1986, ApJ, 305, 45

Discussion

R. Barvainis: Do you think it is possible, in order to explain the flat optical/UV spectrum in radio quiet quasars, that the cold filaments or a cold irradiated disk may be emitting optically thin bremsstrahlung rather than blackbody radiation?

M. Begelman: I have not gone through the details, but I suspect that it would be difficult to make this work. The balance between bremsstrahlung cooling and X-ray heating tends to be thermally unstable, thus when bremsstrahlung is dominant over other cooling processes (e.g., collisional excitation) the gas tends to undergo runaway heating. Also, bremsstrahlung is such an inefficient cooling mechanism that it would probably require a large column density in order to get enough emission measure. In order for the X-rays to penetrate to a sufficient depth *and* keep the gas highly ionized would require such a large ionization parameter that the gas would heat up.

M. Sitko: Isn't the spectrum of a single-temperature blackbody too narrow to fit the blue bump spectra in most QSOs?

M. Begelman: Yes. In all of the models I've described there would be a range of blackbody temperatures depending on geometric structure and extent of both the radiation source and the reprocessing cold gas. Superposition of the spectra would lead to a broader bump, as in standard accretion disk models. Further broadening could result from incomplete thermalization and Comptonization.

S.Tsuruta: Even if the observed short timescale variability is local, don't you think that the emitting region cannot be too large, e.g., very large amplitude hourly (or less) variations cannot be produced in the BLR?

M. Begelman: Yes, I suspect that is true. It is hard to see how energy could be stored and released in such a concentrated form at that distance.

J. Webb: In regards to the flare-corona model, for objects such as 0235+164, the energy released during a major optical flare is too large to be stored in a magnetized disk (Shields and Wheeler model) in the time between typical outbursts. This problem can be alleviated by invoking relativistic beaming. Do you see any reason why flares in this model should be relativistically beamed?

M. Begelman: I don't think one can rule out the possibility that relativistic motions occur in the flares. As for placing these flares in the context of earlier disk models, I have tried to emphasize that disks in AGNs may be very different from the prevailing view.

K. Horne: Instead of collisions between magnetically confined filaments, could you not obtain similar variability phenomena from collisions between pairs of stars and/or stellar winds? For example, the crossing time for $R_* \sim 10^{11}$ cm, $\Delta v \sim 3\times10^8$ cm s^{-1} is $\Delta t \sim 300$ s. You might produce a sharp pulse of X-ray emission at the time of closest approach between the colliding stellar winds, and make the Fe Kα by reprocessing in the denser layers of the two stars.

M. Begelman: Because of optical depth effects, velocities even higher than your estimates may be necessary to get the observed $\Delta L/\Delta t$. Collisions between stars at such high velocities are thought to be highly disruptive, so there is a question of survival. This might not be so severe if the collisions were mainly between stellar winds or envelopes at radii much larger than R_*. The envelopes would have to be optically thick to X-rays in order to provide enough reprocessing, and the flare duration might be too long.

M. Penston: One of the best arguments against the AGN models of Roberto Terlevich which do not involve black holes has been the rapidity of the X-ray variations. I am intrigued by the local flaring model for X-rays you have described. In such a case, are black holes necessary?

M. Begelman: The local flaring interpretation does weaken the connection between variability time scales and the size of the central engine. However, the characteristic energy densities and velocities indicated by the flaring model still suggest that a black hole is at the center of it all. How would a stellar model arrange a flare containing 10^{45} ergs (the output of a 100 $M_\odot$ star in 10^5 sec) lasting only 100 sec unless the stars are physically colliding at near-relativistic speeds?