MULTIFREQUENCY VARIABILITY OF AGN'S

Continuum variations from the near IR to the X-rays

J. CLAVEL
ESA, ESTEC/SAI Postbus 299
2200-AG Noordwijk, The Netherlands.

1. Introduction

Because they emit copiously over more than 10 decades in frequency, Active Galactic Nuclei (**AGN**) cannot be understood without the help of multiwavelength observations. On the other hand, variability monitoring has also proven to be invaluable in understanding the continuum and line emission process as well as the geometry of the innermost regions in these objects. Indeed, at the heart of **AGN**'s lies an object which is so compact that the only way to probe its structure is the study of the temporal evolution of its spectrum. The equivalent resolution which can be achieved in this way is of the order of 10 microarcsecs, far beyond the capability of any UV or optical telescope.

The techniques used are fairly straightforward in their principle, but extremely demanding in practice. The holly grail of variability studies are correlated variability between different emission or absorption components. Correlated variability strongly suggests and is often taken as a proof of a causal link between the components. For instance, if emission lines are found to vary together with the continuum, this suggests that the emission line gas is heated and photoionized by the continuum photons. Applying the usual cross-correlation techniques, it is straightforward to measure the the time shift between the two time series and therefore the distance between the corresponding emitting regions. For instance, if the emission line time series is found to be shifted by + 10 days *w.r.t.* that of the continuum, then the gas is likely to lie at a mean distance of the order of 10 lt-d from the continuum source. The variability monitoring techniques even allows us to distinguish between different types of geometry. For that purpose, one needs to reconstruct the Transfer Function (**TF**) of the correlated time series. The **TF** describes the response of an emission line to a δ-function continuum burst. Suppose for instance that the gas is concentrated in a disk seen face-on and whose inner and outer radii are respectively r_{min} and r_{max}. It is easy to show then that the **TF** will be zero everywhere except between $\tau = r_{min}/c$ and $\tau = r_{max}/c$. By contrast, the TF of a thick spherical shell has a flat maximum in the range $0 \leq \tau \leq 2r_{min}/c$ and decreases monotonically to zero at $2r_{max}/c$.

There are formidable logistical obstacles in applying the cross-correlation and TF reconstruction techniques. The fundamental problem is to obtain time series

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which are long compared to the average time scale of variability τ and with a sampling interval much shorter than τ. In practice, for a moderately luminous Seyfert I galaxy such as NGC 5548, one needs to measure its flux at every 4 days or more during at least 8 months. The amount of observing time necessary to carry-out such a programme rapidly becomes prohibitive. Even if the time is granted, one must still make sure that the observations are scheduled at a regular interval and that there are no gaps in the time series. A couple of weeks of bad weather can easily kill such a project. Moreover, one needs the source to be cooperative in the sense that its variation must be large compared to the typical flux measurement errors. Systematic errors which affect the photometric quality of the data - such as fluctuations in the transparency of the atmosphere or seeing variations which change the relative amount of dilution by stellar light - must also be minimized. These criteria calls for UV monitoring since (1) variations in the space ultraviolet are larger than at other wavelengths (2) one is essentially free from stellar contamination below 3000 Å (3) space observations are unhampered by the earth atmosphere and bad weather. Not surprisingly therefore, the most successful such programmes have been carried-out with the IUE satellite. Of course, the logistical obstacles become an order of magnitude worse when one tries to coordinate observations across different wavebands using different satellites and ground based facilities.

In this review, I will summarize those results obtained from the few multifrequency monitoring campaigns which have been carried-out so far. Because, these data yield information mainly about the continuum emission processes, I will leave aside the results obtained on the emission lines, except where they have a direct relevance to the question of the origin of the continuum. The emission line data have been reviewed recently in a recent and excellent article by Peterson (Peterson, 1993). I will concentrate on "normal" **AGN**'s and shall not discuss "blazars" since these are the subject of another presentation at this conference ((Maraschi, 1993)).

2. UV & Optical variability: constraints on accretion disk models

Because the UV and optical variability data bear on accretion disk models, it is worth reviewing briefly the status of accretion disk models in the context of **AGN**'s.

Since the pioneering works of Lynden-Bell (Lynden-Bell, 1969), Shakura & Sunyaev (Shakura & Sunyaev, 1973) and Shields (Shields, 1978), modeling the Spectral Energy Distribution (**SED**) of **AGN**'s in terms of thermal emission from an Accretion Disk (**AD**) surrounding a massive Black-Hole has become a kind of industry. Geometrically thin optically thick **AD** model are generally successful at fitting the optical & Ultraviolet part of the **SED**, the so-called "big-bump" (see (Malkan, 1991) and references therein, and more recently (Rokaki *et al*, 1992)). Leaving aside the fact that this success is by no mean a proof of the existence of thin AD in **AGN**'s, this model is plagued by fundamental problems which have been summarized in

(Courvoisier & Clavel, 1991), namely:

- There are now 4 high redshift **QSO**'s for which the **EUV SED** is observed to rise sharply up to about 3 Ryd, making the disk supper-Eddington by nearly an order of magnitude (Reimers *et al*, 1991) (Jakobsen *et al*, 1993) (Lyons *et al*, 1993).
- In the **LTE** approximation at least, thin **AD** should show a strong discontinuity at the Lyman limit. Such a discontinuity has never been observed with a 15 % stringent upper limit (Antonucci Kinney & Ford, 1989) (Koratkar Kinney & Bohlin, 1992).

There are now several **AGN**'s whose variations have been well sampled contemporaneously at optical (~ 5200 Å) and ultraviolet (~ 1400 Å) frequencies. These are NGC 5548 (Clavel *et al*, 1991) (Peterson *et al*, 1991), NGC 4151 (Clavel *et al*, 1990), NGC 3783 (Reichert *et al*, 1993), (Stirpe *et al*, 1993), 3C 273 (Courvoisier *et al*, 1990) and Fairall 9 (Clavel Wamsteker & Glass, 1989). Surprisingly, in all 5 **AGN**'s the various UV and optical continuum band vary in phase with no measurable delay. In Fairall 9, the simultaneity of the variations extends up to 1.2 μ. This is clearly illustrated in Fig.1 & Fig.2. Fig.1 shows the light-curves of various continuum bands and emission lines in NGC 5548 together with the corresponding cross-correlations. The cross-correlations of the optical continuum (upper panel) and H_β emission line (middle panel) with the UV continuum of NGC 3783 are shown in Fig.2. In both sources, it is obvious that, in contrast to the emission lines where a clear lag is present, the optical continuum varies in phase with the UV flux. The upper limits on the delay of the optical flux are quite stringent, *e.g.* ≤ 2 days in NGC 5548 and ≤ 1 day in NGC 3783.

Such a finding is in complete contradiction with the thin disk model. In a thin **AD**, the effective radius of the optically emitting region is about 7 times larger than that of the UV-emitting layer. Since the two regions cannot communicate faster than the sound speed, it is easy to show that the optical should lag the UV by several years. This is true even if the disk is supported by the radiation pressure rather than the gas pressure, the opacity of the disk being so large that the photon diffusion time remains several orders of magnitude than the observed 1-2 days upper limits. In fact, these upper limits suggest that the UV and optical layer are synchronized by an external signal travelling at a speed which is more than 10 % the velocity of light.

3. Correlated UV & X-ray variability: evidence for thermal reprocessing

Further insight into that problem can be gained from simultaneous monitoring of the UV and X-ray flux. Only 4 sources have been the subject of such correlated studies: NGC 5548 (Clavel *et al*, 1992), NGC 4151 (Perola *et al*, 1986) and to a lesser extent, Fairall 9 (Morini *et al*, 1986) and NGC 4593 (Santos-Lleo *et al*, 1993). As can be seen in Fig.3, the 2–10 keV flux and 1350 Å continuum are clearly

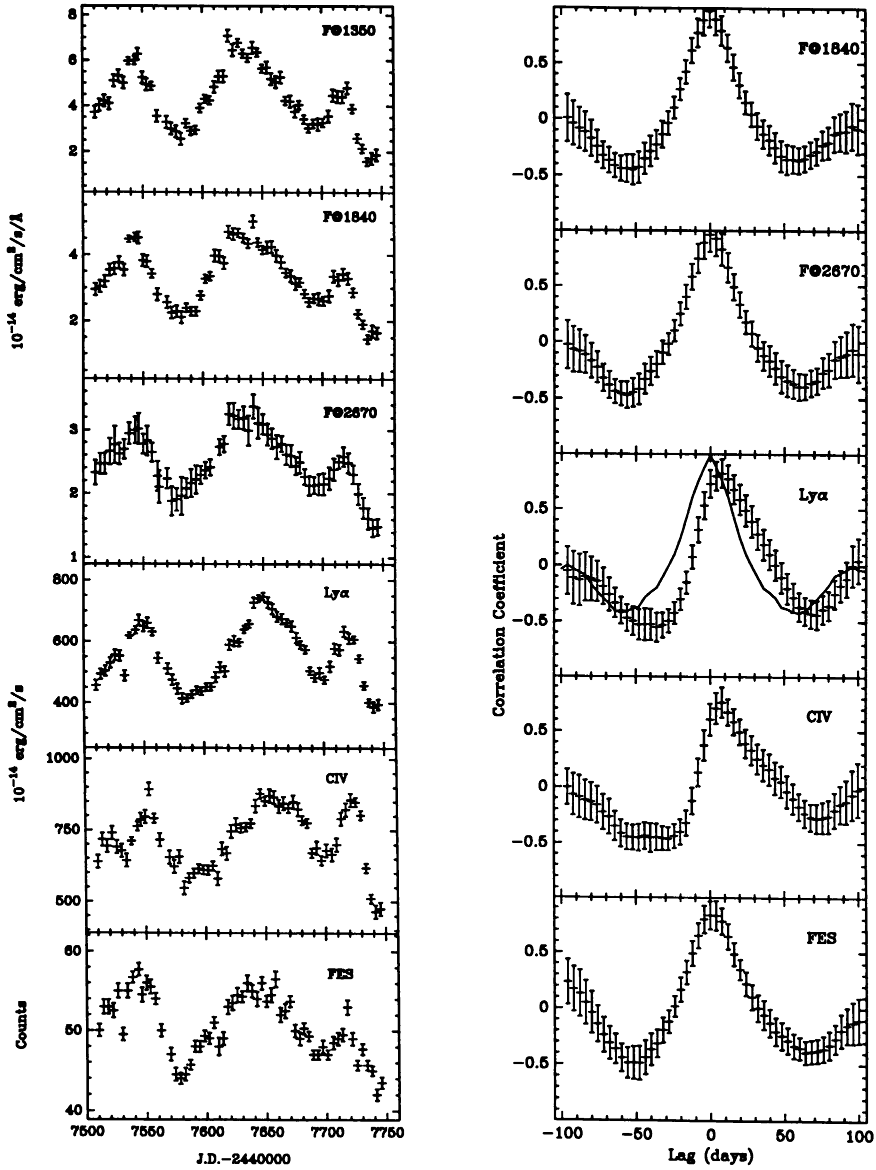

Fig. 1. Left: the light curves of various continuum bands at 1350 Å 1840 Å and 2670 Å) & 5200 Å ("FES") bands and emission lines (Lyα1216, CIV1549) in NGC5548. Right: the corresponding cross-correlations w.r.t. the 1350 Å flux

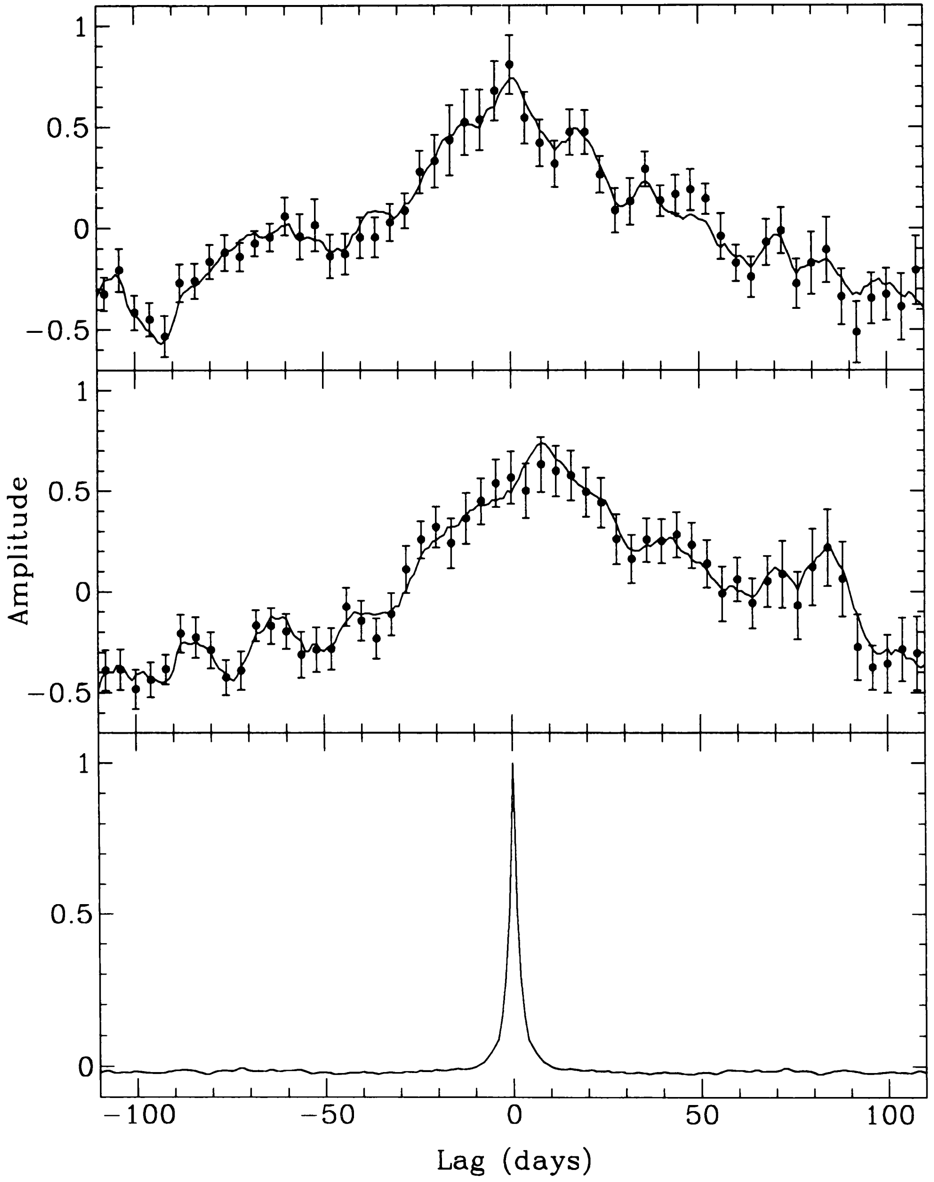

Fig. 2. The cross-correlations of the optical continuum (upper panel) and H_β emission line (middle panel) with the UV continuum in NGC 3783. The bottom panel shows the auto-correlation function of the sampling pattern.

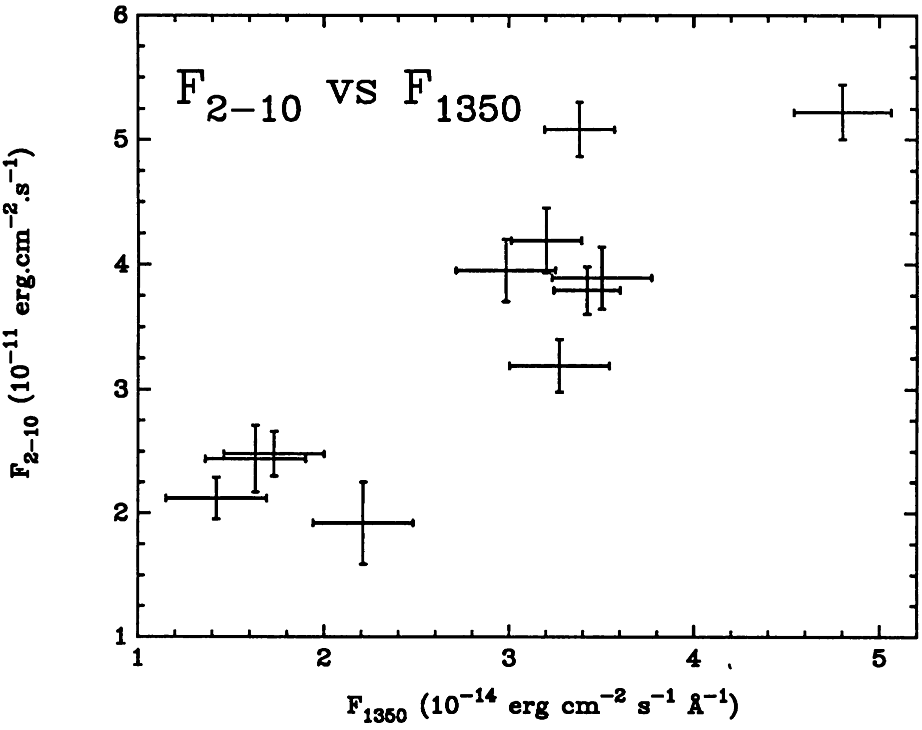

Fig. 3. The 2–10 keV flux as a function of the 1350 Å continuum in NGC 5548

correlated in NGC 5548, and the best-fit regression line goes through the origin, implying that the UV flux varies in direct proportion to the X-rays. Furthermore, a cross-correlation analysis shows that there is no measurable delay ($\Delta t \leq 6$ days) between the 2 bands. A correlation is also present in the 3 other sources.

To understand the meaning of this correlation, it is necessary to put it in the context of other observational results obtained in the X-ray regime. X-ray observations with the GINGA satellite (Pounds *et al*, 1990), (Nandra *et al*, 1991a) show that the presence of a strong Fe Kα emission line and a hard X-ray "hump" above 10 keV is a common property of Seyfert galaxies. Both features have been interpreted as evidence for reprocessing of the X-ray spectrum. In this scenario (Georges & Fabian, 1991), the X-rays illuminate a disk of cold gas. Ninety percent of the incident flux is absorbed, but a small fraction is compton scattered back ("reflected") to the observer, thereby creating a broad hump in the spectrum with a maximum around 20 keV. Part of the absorbed flux is re-emitted in the form of Fe Kα emission line photons. The reprocessing model makes one implicit prediction. The 90 % of the X-ray flux that is absorbed generates heat inside the disk. This energy must reappear in the form of thermal emission at frequencies which depend on the effective temperature of the reprocessing medium. Since the latter is of the order of a few 10^5 K (as can be inferred from the energy of the Kα line and iron edge), this is likely to take place in the ultraviolet and extreme ultraviolet region of the spectrum. Furthermore, given the high density of the gas, the absorption and re-emission are essentially instantaneous. Hence, the reprocessing model implicitly predicts that the variations of the X-ray and UV spectrum should be correlated. The correlation does not need to be perfect however. A perfect correlation would imply an implausibly fine tuning, with the light travel time of the X-ray photons matching very closely the characteristic time scale of variability of the X-ray source.

Hence, the correlation of the hard X-rays and UV flux observed in NGC 5548, NGC 4151, NGC 4593 and Fairall 9 can be understood as a consequence of the the X-ray absorption by the disk followed by thermal UV re-emission. Furthermore, the thermal re-emission will also occur at optical wavelength. Hence, the quasi-simultaneity of the UV and optical variability discussed previously can be readily explained with this model. In other words, all available data suggest that the variations of the entire UV-optical spectrum are driven by those of the hard X-rays.

The observed UV/X-ray correlation is far from perfect, as expected in this model. The fastest X-ray variations recorded in NGC 5548 correspond to ~ 30 % fluctuations of the flux in ~ 5 hours (Nandra *et al*, 1991b). Such rapid variations have never been observed in the ultraviolet, the PDS of the UV light-curve being steep with little or no power on time scales shorter than 1 day (Clavel *et al*, 1991). In the thermal reprocessing scenario, this implies that the travel time of the X-ray photons is at least of the order of a few times 5 hours, say 1 day. If we combine this lower limit with the observed 6 days upper limit on the delay of the UV flux and translate them into distances, we obtain:

$$2.5\ 10^{15} \leq \mathrm{D} \leq 1.5\ 10^{16}\mathrm{cm}$$

where D is the average distance between the X-ray source and that part of the disk which does the bulk of the thermal reprocessing. How does this compare with the dimension expected from the accretion disk in NGC 5548 ? One can combine the BLR effective radius inferred from the delay in the response of the emission lines to the continuum variations together with the mean velocity of the gas measured from the line width to estimate the mass of the black-hole in NGC 5548 (Clavel *et al*, 1991). Under the assumption that the gas is gravitationally bound, one obtains $\mathrm{M} = 3.7\ 10^7\ \mathrm{M}_\odot$. This in turns implies that the thermal reprocessing region lies between 225 and 1350 Schwarzschild radii from the X-ray source. This is one to two orders of magnitude larger than the theoretical size of the 1350 Å emitting region on a standard α disk without reprocessing.

An independent way of estimating D comes from the energy distribution itself. Indeed, the fact that the UV varies in strict proportion to the X-rays is consistent with the hypothesis that the entire ultraviolet flux – at least at the time of the monitoring campaigns in 1989 and 1990 – originates from reprocessing of the X-ray photons absorbed in the disk. From the variability time scale, we know that the X-ray source is much more compact than the reprocessing region. The Equivalent Width EW of the Fe Kα line also requires that the disk covers essentially $2\,\pi$ as seen from the X-ray source. In addition, there is no hint of the strong X-ray absorption at low energy that would be expected if the X-ray source was lying behind or was partially embedded in the reprocessing medium. All these observables calls for a special geometry where the X-ray source lies above the disk, perhaps at the base of the radio jet. The energy distribution of the thermally reprocessed radiation then depends on D, the distance of the X-ray source to the reprocessing medium. This distance can be expressed as a function of the height H of the X-ray source above the disk and the mean effective radius R of the reprocessing ring in the disk, $D = \sqrt{H^2 + R^2}$. For illustrative purpose, let us consider the two extreme cases. In the first case, $H \gg R$, *i.e* the height of the X-ray source above the disk is much larger than the dimension of the disk itself, at least up to its UV and optical emitting layers. The heating rate per unit surface area of the disk is diluted by the usual D^{-2} factor and it is then easy to show that the effective temperature goes as $T_{eff} \propto R^{-1/2}$ instead of the usual $R^{-3/4}$ dependency in a disk without reprocessing. The emerging spectrum has a frequency spectral index $\alpha = -1$ ($F_\nu \propto \nu^\alpha$). The opposite case is where $H \leq R$. In that case, the above dilution factor is multiplied by a $\cos\theta$ term, where $\theta = \arctan\frac{H}{R}$ is the complement to the angle of incidence of the X-rays onto the disk. One can easily show that in this case, the heating rate recovers its usual $R^{-3/4}$ dependency and the emerging spectrum is the same as that of a disk without external heating *i.e.* $F_\nu \propto \nu^{1/3}$. The fact that the spectral index of NGC 5548 varies around an average value of -0.7 suggests that the actual situation is intermediate between those two extreme cases, but is probably closer to case (1) than case (2), *i.e.* $H \geq R$. Detailed calculation of the emergent spectrum from an externally heated disk (Rokaki *et al*, 1992) show that that the best fit to the NGC 5548 Ultraviolet energy distribution is obtained for $250\ R_s \leq H \leq 1000\ R_s$. It is reassuring that these limits are entirely consistent with the limits on H derived from variability argument.

To make further progress, it will be extremely important to restrict the range of allowed values for H. This can only be achieved with simultaneous X-ray & UV monitoring campaigns that have a much better temporal resolution than previous campaigns. This is precisely the goal of the upcoming observing programme of NGC 4151 which the AGN watch collaboration will undertake in November-December 1993. This AGN will be observed with IUE and CGRO continuously during 10 days, while in the same period ROSAT and ASCA will take repeated measurements of its X and γ ray spectrum. **ROSAT** will observe every 12 hours. This will hopefully be sufficient to pin down the delay in the response of the UV flux to the X-ray fluctuations and therefore the height of the X-ray source above the disk.

The thermal reprocessing model also seem to solve the problems which plague the thin **AD** model. X-ray heating from above reduces the temperature gradient in the upper layers of the disk and may therefore weaken or suppress the Lyman Absorption edge. Adding externally supplied energy means that the energy distribution of the "big-bump" can be accounted for with a smaller black-hole mass than in disk models without reprocessing (Malkan, 1991). A smaller central mass allows the disk to be hotter so that its spectrum may extend up to 3 Ryd – as observed in a few high z QSO's – without becoming supper-Eddington. As a matter of fact, if the X-rays are generated outside the accretion flow – in a jet or wind, for instance – their luminosity (and therefore that of the heated disk) is not constrained by the Eddington limit.

The thermal reprocessing model faces a serious energetic problem, however. During the 1989 and 1990 campaigns, there was just enough X-ray flux in NGC 5548 over the 2–100 keV range to power its UV spectrum (Clavel *et al*, 1992). Since **CGRO** and **SIGMA** observations consistently show that the hard X-ray spectrum of Seyfert I galaxies bends steeply above 100 keV (Jourdain *et al*, 1992); (Cameron *et al*, 1993); (Maisack *et al*, 1993), one does not solve the problem by extending the integration range. In 1989 and 1990, the UV spectrum of NGC 5548 was in a medium to low state and the correlation between the X-ray and UV flux holds with the same slope over all time scales from 6 days up to ~ one year. However, on May 21, 1984 when the UV flux reached an historical maximum about 3.5 times higher than the 1990 average, the X-rays as measured by **EXOSAT** were only 70 % stronger, not enough to account for the energy in the "big-bump". The same situation applies to NGC 4151 (Perola *et al*, 1986): the X-ray/UV correlation holds with the same slope over time scales from a few days to ~ one year in 1983 and 1984 when the source was moderately bright, but breaks down during a very large UV outburst in May 1979 when the X-ray flux recorded by **EINSTEIN** was at about the same level as in 1983. In other words, in both NGC 5548 and NGC 4151, the correlation saturates during large outbursts of the ultraviolet flux in such a way that there is a deficiency of X-rays to account for the energy in the "big-bump". This may indicate that the thermal reprocessing model only applies to moderate amplitude (factor of ~ 4) variations of the ultraviolet flux and that another explanation has be found for very large UV bursts. The May 1984 outburst of NGC 5548 was unusual in that it took several months to develop. Such a time scale is compatible with the burst originating from thermal instability in the disk (Clavel *et al*, 1992).

For **QSO**'s, however, the problem of the energetic becomes overwhelming. This is because statistical studies of large samples show that the X-ray luminosity increases less than linearly with the optical-UV luminosity, *i.e.* $L_x \propto L_{opt}^{0.8}$ (Avni & Tananbaum, 1986). In other words, Quasars are X-ray deficient so that, in the reprocessing scheme, they lack the amount of high energy radiation necessary to power their prominent ultraviolet "big-bump". Interestingly enough, Quasars do not seem to show much evidence for reprocessing – such as the Fe Kα line or the compton reflection "hump" –in their X-ray spectra either (Williams *et al*, 1992). It is also worth recalling that the pattern of variability of the UV-optical spectrum of quasars is different from that of the lower luminosity Seyfert I galaxies, the amplitude of their variations being relatively small and the time scales long (Maoz *et al*, 1993); (Kinney *et al*, 1991). This suggests that the "big-bump" of QSO's originates from viscous dissipation inside the disk, in contrast to Seyfert's where it is driven by X-ray heating. It is of course not satisfactory to invoke different emission mechanisms in such two so phenomenologically similar classes of objects, the more so because one is now left with no explanation for the absence of a Lyman discontinuity and the super-Eddington SED in quasars. Alternatively, it is possible to solve the energy budget problem if the X-ray emission is not isotropic in such a way that the disk receives more flux than the observer. A partially reflecting screen of hot electrons (*i.e.* the "warm absorber") could do the job of scattering the X-ray photons back onto the disk. One is then left with the problem of explaining why this screen should be more efficient in high luminosity quasars than in Seyfert's. Another possibility is the completely different model proposed by Ferland where the "big-bump" arises from optically thin free-free emission in a hot plasma heated by X-rays (Ferland Korista & Peterson, 199o) (Barvainis, 1993).

4. Ultraviolet & IR monitoring: mapping the molecular Torus

The ultraviolet (1200–3200 Å) optical and near IR (JHKL) spectrum of the high luminosity Seyfert I galaxy Fairall 9 has been extensively monitored from 1978 up to 1986 (Clavel Wamsteker & Glass, 1989). Dramatic variability was observed, the 1340 Å flux decreasing by a factor $\sim$ 30 in a few years. Though the variations were milder in the optical and in the J Band, they nevertheless tracked closely those of the UV continuum, as already mentioned in the previous section. However, the IR flux at wavelengths longer than 1.2 μ lags behind the Ultraviolet. Moreover, as can be seen from the cross-correlations of Fig.4, the delay increases systematically with wavelength, from 250 days at 1.6 μ, to 385 days at 2.1 μ and 410 days at 3.4 μ. Also, the amplitude of the near IR variations peak at 2.1 μ.

Such a pattern is precisely that expected if the near IR radiation originates from thermal re-emission by dust grains heated by the ultraviolet photons (Clavel Wamsteker & Glass, 1989). The observed delay implies that the dust shell lies at 350 ± 100 lt-d from the UV source. Using the observed mean luminosity of Fairall 9, one can compute the equilibrium temperature of the grains at such a distance: $T_{dust} = 1730 \pm 230$ K. This is in excellent agreement with the observed colour temperature of the variable IR component and the fact that it peaks at 2.1 μ. Within the theoretical and observational errors, such a temperature is equal to the sublimation temperature of graphite, the most refractory of all possible dust constituents (Rudy & Puetter, 1982). Detail calculations of a dust model

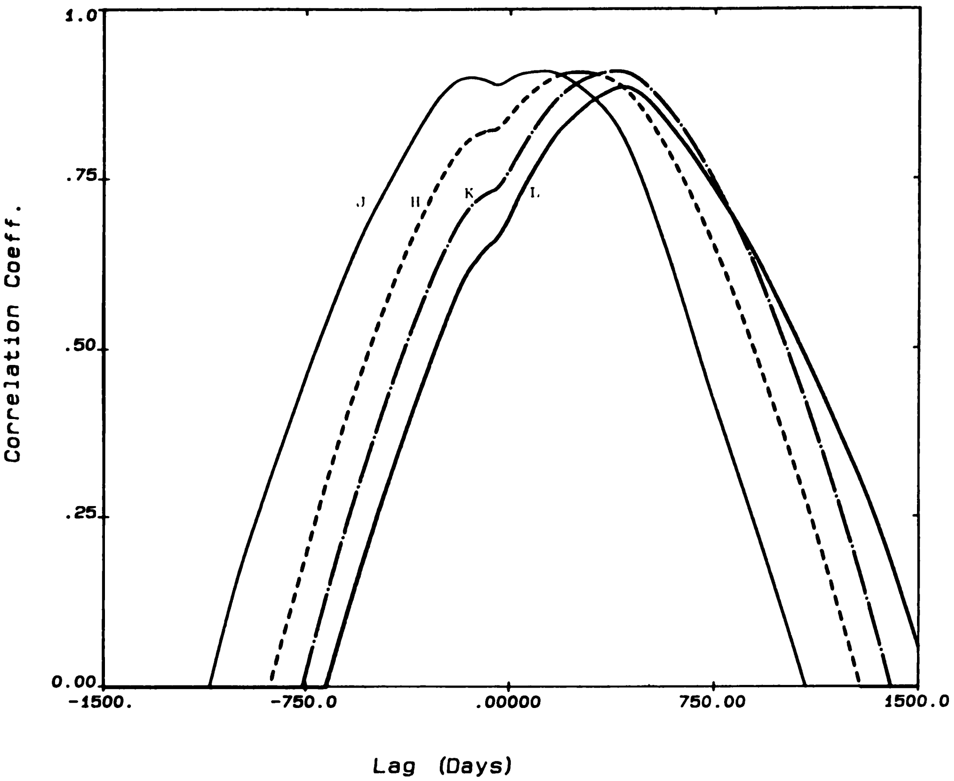

Fig. 4. The cross-correlation of the IR flux in the J H K & L band with the 1338 Å continuum in Fairall 9. The lag clearly increases with increasing wavelength, from 0 at 1.2 μ to 410 days at 3.4 μ.

applicable to the Fairall 9 data confirm and extend the conclusions of Clavel and collaborators (Barvainis, 1992).

The Lyα1216, CIV1549 and MgII2798 emission line intensities in Fairall 9 also varied with a large amplitude (factor ~ 10), and their variations closely tracked those of the UV continuum with a delay of 155 ± 45 days (Clavel Wamsteker & Glass, 1989). This suggests an effective radius of the order of half a light year for the BLR in Fairall 9, a factor 2 smaller than that of the dust shell. Since the dust shell is outside the BLR but well inside the much more extended Narrow Line Region (NLR), it is tempting to postulate that it lies at the inner edge of the putative molecular Torus which is thought to surround the BLR in AGN's. Moreover, the fact that the dust temperature is equal to that at which graphite grains sublimate further suggests that the inner edge of the Torus is being evaporated by the intense nuclear radiation field, as postulated by theoretical models of the Torus (Krolik & Begelman, 1986). In these models, the evaporation gives rise to an outflowing wind which creates a high latitude screen of hot electrons. This screen acts as a mirror which reflects the nuclear spectrum back to the observer. In Seyfert II's, the Torus is viewed edge-on, the nucleus is obscured and one only sees the reflected nuclear spectrum in polarized light (Antonnuci & Miller, 1985). In Seyfert I's, one has a direct unhindered view of the nucleus and the Torus is otherwise undetectable. Fairall 9 may be the first example of a Seyfert I galaxy for which the Torus leaves a clear imprint on its spectrum. AGN's such NGC 4151 (Bromage *et al*, 1985) and OI 287 (Antonnuci Kinney & Hurt, 1993), with their blue shifted absorption lines and relatively large polarization, may represent intermediate objects where one sees the nucleus through the base of the wind.

There exist a few other AGN's for which near IR variability data - though not as compelling as those of Fairall 9 - strongly suggest the existence of a dust shell irradiated by the UV source. The best such case is NGC 3783 in which a correlation between the U and K band yields an effective radius of 80 lt-d for the dust shell (Glass, 1992). Note that NGC 3783 has a much lower luminosity than Fairall 9 so that one expects a smaller evaporation radius, as is observed. Another good candidate is GQ Com, a fairly luminous Seyfert I galaxy, in which the IR flux is found to lag behind the UV by $\sim$ 250 days (Sitko, 1991). The last object is the low luminosity Seyfert I galaxy NGC 1566, where the time scale of variability of the near IR flux suggests a radius of about 50 lt-d (Baribaud *et al*, 1992).

There is currently no direct evidence for the existence of the molecular Torus. Molecular lines and bands have been observed in the spectra of a several AGN's but it is impossible to decide whether they originate from the Torus or from the Interstellar medium (ISM) of the galaxy. A decisive proof would be the detection of variations in the intensity of those molecular features on time scales of a few months to one year. Unlike the ISM, the gas in the Torus is expected to be relatively warm with temperatures in the range 500–1000 K. These rather unusual conditions should favor the emergence of selected spectral features such as the H_2 mid-J rotational lines in the 3–10 μ range or the CO mid-J rotational band at 4.6 μ. Other good candidates are the Polycyclic Aromatic Hydrocarbon (PAH) bands at 3.3, 6.2, 7.7, 8.6 and 11.3 μ. By monitoring the temporal evolution of these features and using the reverberation mapping techniques described here, it may be possible to study in detail the spatial extent and the physical conditions of the gas inside the molecular Torus. Such programmes will be extremely challenging but are within the reach of the upcoming ISO satellite.

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