JOINT DISCUSSION NO. 6

ACTIVE GALACTIC NUCLEI

(Commissions 28, 40 and 48)

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OPTICAL, INFRARED AND ULTRAVIOLET OBSERVATIONS OF ACTIVE NUCLEI

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1. Introduction

I have been invited to present a brief review of optical, infrared and ultraviolet observations of active nuclei. I will only describe a small sub-set of these observations, in particular those which I believe are most likely to be important in elucidating the properties of the central energy source to which we attribute the origin of all high energy phenomena. I will therefore restrict my remarks to certain aspects of BL Lac objects, optically violently variable quasars, quasars, Seyfert I galaxies and broad line radio galaxies. If we could understand these systems, we should be able to account for most other types of active nuclei, the Seyfert II galaxies, narrow line radio galaxies, all other types of Markarian galaxy, compact blue galaxy, etc. In my view, the recent observations of NGC 4151 provide us with a benchmark against which we should measure all other observations of active nuclei.

2. The NGC 4151 Story

The recent IUE observations of NGC 4151 have been carried out by a large European consortium of observers, known as the EEC (European Extragalactic Collaboration). The figures were kindly provided by Dr Michael Penston who described these results at the recent 3rd European IUE Symposium (Penston 1982). It has long been known that NGC 4151 is a Seyfert 1½ galaxy in the sense that the emission lines contain both broad and narrow components. It is also well known that the continuum and broad emission lines are variable so that the galaxy can change from being a Seyfert I to a Seyfert II galaxy. This is demonstrated in Figure 1 which shows IUE observations of the CIV λ1550, CIII]λ1909 and MgII λ2800 lines made on the 19 October 1978 and 21 April 1980. The earlier observations show what is known as the "high state" in which strong broad line and continuum components are present; in the low state, this broad emission line spectrum is very weak.

Many fascinating results have been obtained from the systematic monitoring of NGC 4151 by IUE. As of earlier this year data from 31 epochs have

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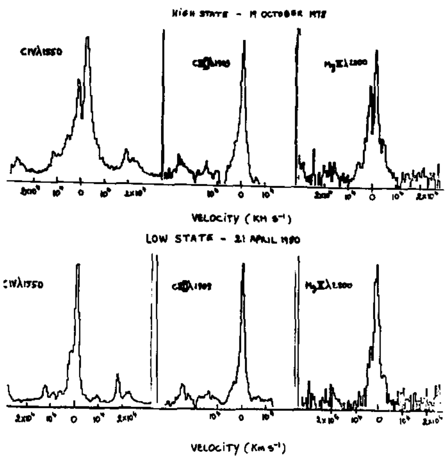

Figure 1. Observations of the CIV, CIII] and MgII lines of NGC 4151 made by IUE on 19 October 1978 and 21 April 1980 (EEC consortium, Penston 1982).

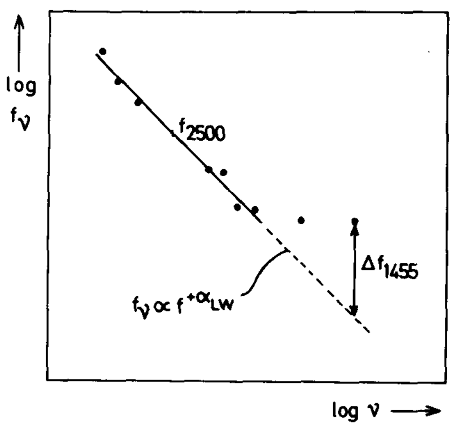

Figure 2. Illustrating the method of analysis of the continuum spectrum of NGC 4151 (EEC consortium, Penston 1982).

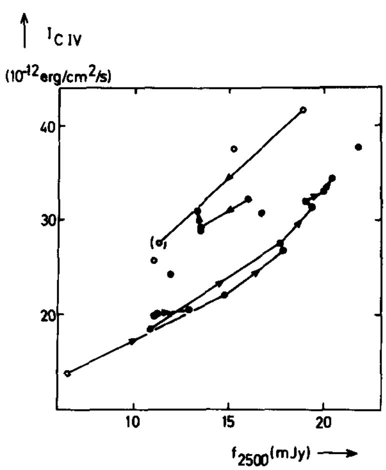

Figure 3. Variations of the intensity of the continuum and the broad component of the CIV line in NGC 4151. The arrows indicate the direction of increasing time. (EEC consortium, Penston 1982).

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been analysed. The method of analysis is indicated in Figure 2 which shows the decomposition of the continuum spectrum into a power-law component at long ultraviolet wavelengths ($2000 < \lambda < 3000\text{Å}$) with spectral index α_{LW} and an excess short wavelength component which is parameterised by the quantity Δf_{1455} shown in the figure. The short wave component associated with Δf_{1455} *must be separate from that associated with the* long wavelength component because it exhibits less variability. It has been shown that the intensity of the continuum radiation and the spectral index α_{LW} are strongly correlated.

Perhaps the most intriguing results have come from the correlated variability of the continuum radiation and the strength of the broad lines. These are strongly correlated in the sense that the stronger the continuum radiation, the more prominent the broad line component. This is convincing evidence for photoionisation models of the excitation of the broad line regions. However, even more exciting is the result that there appears to be a delay between increases in the continuum radiation and the onset of the increase in the intensity of the broad line. This is illustrated in Figure 3 which shows the correlation between the intensities of the CIV line and the continuum, the arrows indicating the direction of increasing time. It is striking that there is a "hysteresis" effect, the variations of the line intensity following variations in the continuum but with a time-lag. This can be readily explained by the photoionisation model illustrated in Figure 4 in which the time-delay gives direct information about the distance of the emission line region from the nucleus. In addition, from the breadths of the broad emission lines, we can estimate the characteristic velocity within the broad line region Δv.

We can therefore find the mass of the central object by application of Kepler's law in the form.

$$M \approx \frac{r}{3} \left(\frac{v}{c}\right)^2 M_{\odot}$$

where r is measured in km. Inserting the appropriate values of the radius of the broad line region and the velocity dispersion, we obtain masses $M \sim 10^8 M_{\odot}$ in excellent agreement with many people's preconceived notions of the masses of active nuclei.

One can go further and speculate about the origin of the far ultraviolet component. Whilst the component appears to be increasing to shorter wavelengths, this cannot continue indefinitely or else there would be excessive ultra short wavelength radiation which would produce the wrong types of high excitation emission lines and would provide a poor fit to the observed continuum spectrum. Better agreement is obtained if the component mimics a 30,000 K black body spectrum, i.e. one which cuts off in the far ultraviolet. Such a "bump" component has been noted in 3C 273 and other Seyfert I galaxies (Ulrich et al, 1980, Malkan and Sargent 1982). The temperature of 30,000 K is an interesting value for an accretion disc around a black hole of mass $\sim 10^8 M_{\odot}$. First of all, the simplest models of accretion discs predict that the effective temperature

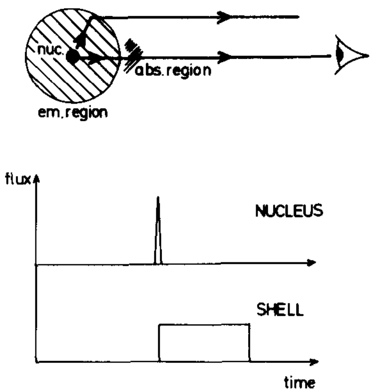

Figure 4. A model for the "hysteresis" behaviour of the correlated variations of the continuum and line intensities in NGC 4151, (EEC consortium, Penston 1982)

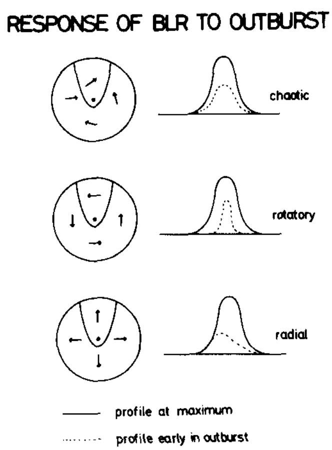

Figure 5. Illustrating how observations of the broad lines of NGC 4151 can distinguish between turbulent, rotational and radial motions during an outburst (EEC consortium, Penston 1982.

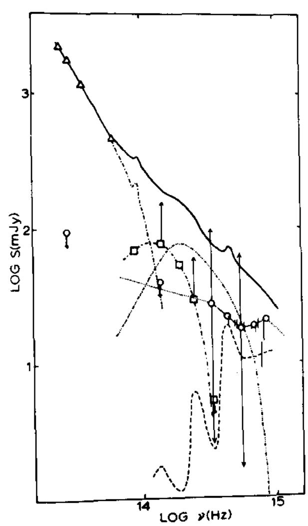

Figure 6. A decomposition of the optical-infrared spectrum of NGC 4151 by Rieke and Lebofsky (1981).

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of the disc should be $T_{eff} \propto (M/M_\odot)^{-1/4}$. Since accretion discs around solar mass black holes radiate in the X-ray waveband, those 10^8 times more massive should have maximum intensity in the far ultraviolet with radiation temperature $\sim 10^5$ K. Second, the intensity of the far ultraviolet emission can be accounted for by the thermal emission of an accretion disc of radius $\sim 10 R_g$ at temperature 30,000 K where R_g is the Schwarzschild radius of a $10^8 M$ black hole. The importance of this argument is that it shows that we have potentially available a means for probing the accretion disc close to the Schwarzschild radius.

Another possibility opened up by this type of observation is the ability to distinguish between rotation, expansion and turbulent motions during the excitation phase of the surrounding gas cloud. This is indicated schematically in figure 5, the sections of the ellipse in each figure indicating the surface seen by a distant observer at a particular instant. Opposite each type of motion is shown the expected instantaneous form of the line profile. According to Penston, the data so far favour a model dominated by turbulent motions although there may also be a small radially out-flowing component.

Of course, all of this story hangs upon the reality of the type of hysteresis phenomenon suggested by figure 3. It is obviously of the greatest importance to confirm these observations in the case of NGC 4151 and to extend them to many more objects. Similar but less extensive observations have been made of other active nuclei and similar phenomena are reported. However, it will require a large, systematic study of many objects of this type to produce a convincing story. Despite my caution in accepting all of this story as fact, these observations open up very exciting possibilities for gaining real knowledge of the very central regions of active nuclei.

3. Other Active Nuclei

Many other studies have now been made of Seyfert I and related galaxies. In a recent preprint by Wu, Boggess and Gull (1982), 20 Seyfert I galaxies have been studied by IUE and these data have been combined with optical spectrophotometry. These observations confirm the "anomolous" ratio of Lyα/Hβ of about 5 as opposed to the value of about 40 to 60 expected of Case B recombination theory. A similar value of Lyα/Hβ is found in NGC 4151.

An interesting result of relevance to the discussion of NGC 4151 concerns the ratio of the CIV to CIII] line strengths. The CIV/CIII] ratio is a sensitive measure of the ionisation parameter U/n_e where U is the energy density of radiation and n_e the electron density. The CIV/CIII] ratio is about 2 for quasars and 5 for type I Seyferts. The interest of these results is that they are not so different from each other and therefore excitation conditions in the broad line regions should be similar. The electron density is more or less fixed by the requirement that only the broad permitted and semi-forbidden lines be observed and consequently because the quasars are intrinsically much stronger sources

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of continuum radiation the location of the broad line regions in quasars must be further away from the nucleus than in a Seyfert galaxy such as NGC 4151. Therefore we would have to look on much longer timescales to observe the same hysteresis phenomena seen in NGC 4151.

There remains the question of whether all the broad line regions in active nuclei are photoionised or whether other excitation processes are important. The observations of Wu, Boggess and Gull (1982) show a correlation between the strengths of the emission lines and the ultra-violet continuum intensity, strongly suggesting the photoionisation picture as in NGC 4151. Indeed in a recent preprint, Ferland and Netzer (1982) suggest that all emission line systems in active nuclei, including even the low-ionisation nuclear emission line galaxies, are examples of photoionisation on the basis of the continuity of these objects with Seyfert galaxies as a function of ionisation parameter.

4. The Continuum Spectrum

A major headache in understanding the continuum spectrum of quasars and the most active systems is the fact that the underlying continuum spectrum appears to contain real broad band "bumps" which necessitate there being multiple components present, each with a fairly narrow broad band spectrum, $\Delta\nu/\nu \sim 1$. An extreme, but possibly not atypical, example is the decomposition of the optical-infrared spectrum of NGC 4151 by Rieke and Lebofsky (1981) (figure 6). This is based upon a wide range of different types of observational data including variability, the presence of various emission features in the continuum spectrum, spectropolarimetry, etc.

Whilst it may eventually be necessary to decompose the spectra of all active nuclei in this way, a broad picture of the basic components needed is provided by the recent series of papers by Allen, Ward, Hyland and their collaborators (1982) who have studied the optical and infrared spectra of a wide range of the active nuclei listed in Section 1.

(a) A necessary component is the underlying continuum spectrum which is presumed to originate close to the energy source itself. We obtain the clearest view of this component in the BL-Lac objects in which the spectra in the optical and near infrared parts of the spectrum can be represented by power-laws with spectral indices $\alpha \sim 0\text{-}3$ ($I_\nu \propto \nu^{-\alpha}$). I have already expressed doubts as to whether all continua are so simple. In the cases of other types of active nuclei such as 3C 273, NGC 4151 and many Seyfert I galaxies, there must be additional "bump" components present.

(b) To obtain a quasar spectrum, one should add on the emission line spectrum and then most of the optical and infrared colours can be broadly understood. An illustration of this is the infrared colour-colour diagram of J-H versus H-K (figure 7). The wavy line shows the expected variation of the colours for a standard quasar spectrum redshifted from

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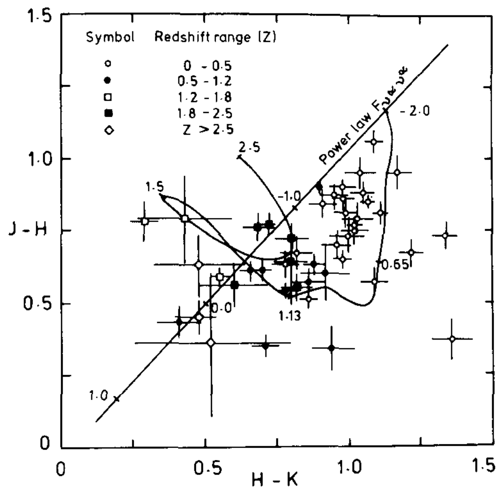

Figure 7. The infrared colour-colour relation for quasars (J-H versus H-K). The predicted relation for a standard quasar spectrum is shown by the wavy line, the redshift of the qausar being indicated on the line (Hyland and Allen 1982).

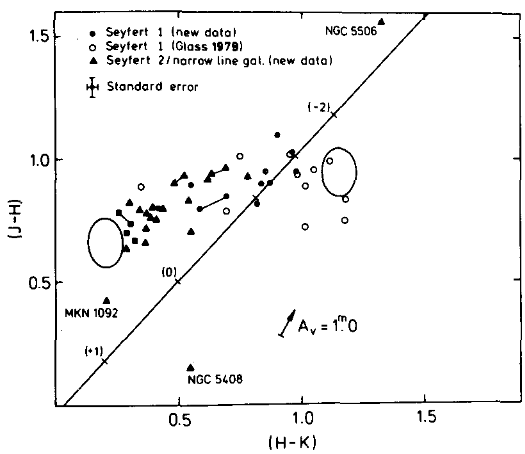

Figure 8. The infrared colour-colour diagram for Seyfert galaxies. The ellipses to the left and centre of the diagram indicate the typical location of galaxies and quasars respectively at small redshifts. (Ward et al, 1982).

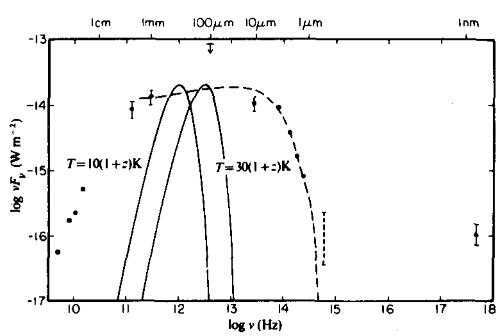

Figure 9. The energy distribution of 1413+135. The dashed curve shows a model for optically thin synchrotron radiation from 1413+135. The solid lines show the thermal emission from dust grains at two representative temperatures. (Beichman et al 1981).

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0 to 2.5. The observed points broadly cluster in the appropriate parts of the diagram at different redshifts. An interesting feature which Allen and his colleagues report is the presence of a "bump" feature at 3μm which they attribute to heated dust in the emission line regions. They claim that the amount of dust required to produce the feature is consistent with reasonable values of the gas-to-dust ratio in the emission line regions.

(c) Then to produce the Seyfert I and II galaxies, one should add on the appropriate amount of stellar continuum radiation. This is illustrated in figure 8 which shows the typical J-H, H-K colours for normal galaxies and quasars as two ellipses to the left and centre of the diagram respectively. Most of the active galaxies can be accounted for by suitable combinations of these two components.

Whilst the picture is reasonably straightforward, it does not get us very much further forward in understanding the origin of the underlying continuum spectrum.

5. Steep Spectrum Objects

Among the more unusual objects discovered recently, has been a class of "infrared quasars". By this is meant the fact that their optical spectra are so steep that much more energy is emitted in the infrared waveband than in the optical. These were first noted by Rieke and Lebofsky (1980), perhaps the most striking example being the source 1413+135 which is illustrated in figure 9 (Beichman et al 1981, Bregman et al 1981). The question which has been asked is "Are these unusual quasars?" In some ways, the answer is "Yes" and in others "No". Taking the negative answer first, they are not especially unusual so far as optical-infrared spectra are concerned. It is now apparent from the work of Impey and Brand (1981) and others that there is a wide range of spectral indices for the optical-infrared spectra of BL-Lac objects and violently variable quasars ranging from about 0 to 3. Objects such as 1413+135 have spectral indices towards the upper end of this range. Thus, almost certainly, the "infrared quasars" are simply extreme examples of the class of BL-Lac or active quasar. An intriguing example of what is now possible in the far infrared waveband from observations with the Kuiper Airborne Observatory has been the detection of 3C 345 at 100μm (Harvey, Wilking and Joy 1982). This shows that it is now possible to measure the total energy output of these infrared quasars.

However, they do have some remarkable properties. Rieke and Lebofsky (1980) drew attention to the fact that the infrared-optical spectrum is just about as steep as is possible from incoherent synchrotron radiation even if there is an abrupt upper energy cut-off in the spectrum of the electrons. Such a fit to the spectrum of 1413+135 is shown in figure 9. Knowing the x-ray luminosity of the source, it is possible to determine rather precisely both the magnetic field and the energy of the electrons radiating at the cut-off frequency. If this is correct, one may have determined rather precisely the magnetic field strength and the energies of the particles in the active nuclei, $B \sim 100$ gauss, $\gamma_{cut-off} = E/m_e c^2 \sim 300$ (Beichman et al 1981).

My worry about these objects is that it is difficult to understand why the spectral index in the optical part of the spectrum does not vary wildly as the source varies in strength. This is because it is very difficult to imagine how one would make the source vary without changing the magnetic field strength or injecting more high energy electrons. In either case, the position of the cut-off in the spectrum should vary in the optical and infrared part of the spectrum leading to strong variations of spectral index. I am surprised this has not been seen yet. If it is not observed something rather strange may be going on in these objects.

6. Superluminal Motion from Optical/Infrared Observations

Finally, we should note evidence from the optical and infrared wavebands that may suggest the necessity for superluminal velocities. It is clearly important to look for evidence independent of the radio VLBI data for such phenomena. There are two basic contributions which have been made from optical and ultraviolet observations to this topic (see Blandford and Rees 1978).

(a) The Variability of BL-Lac Objects The evidence hinges on two inequalities of fairly general applicability to active nuclei. First, the timescales of variations must be longer than R_g/c where R_g is the Schwarzschild radius of the black hole, i.e.

$$\Delta t \gtrsim 10^{-5} \left(\frac{M}{M_\odot}\right) \text{ s}$$

On the other hand, the Eddington luminosity provides an upper limit to the luminosity of a black hole of mass M

$$L \lesssim 10^{38} \left(\frac{M}{M_\odot}\right) \text{ erg s}^{-1}$$

Thus, observation of a particular timescale of variability sets an upper limit to M and consequently to the luminosity L which is varying. This is violated for some BL-Lac objects such as AO 0235+164 and in particular for the object OJ 287 in which variations on the scale of 1 minute have been detected at 1.28μm on one occasion (Wolstencroft, Gilmore and Williams 1982).

One way of avoiding this problem is to suppose that the component is travelling rapidly towards the observer, thus relaxing the limit on Δt and enhancing L by blueshifting the intrinsic luminosity of the source.

(b) Polarisation bursts in BL-Lac Objects In objects such as AO 0235+164, polarisation bursts of short duration have been observed (Impey, Brand and Tapia 1982). Polarisations of up to 44% have been observed indicating the regularity of the magnetic field structures. The problem arises in the following way. In order that most of the emission is emitted in the infrared rather than the x-ray waveband because of inverse Compton scattering, the brightness temperature should be less than about 10^{12}K.

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This means that the magnetic field strength in the source region must be large and consequently the synchrotron half-lives of the particles must be very short. The losses are so strong that these particles can cool to non-relativistic velocities at which they form a cold gas which will depolarise the radiation by Faraday depolarisation.

A way of avoiding this conclusion is again to make the components move relativistically thus increasing the intrinsic size of the region and decreasing the energy densities of radiation in the source regions.

It may well be that relativistic motion has to be evoked to explain optical and infrared properties of active nuclei as well as their radio properties. There is an urgent need for more systematic observations of the most highly variable objects.

Acknowledgements

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