THE INFRARED, OPTICAL AND ULTRAVIOLET PROPERTIES OF ACTIVE NUCLEI

Marie-Helene Ulrich
European Southern Observatory
Garching bei München

ABSTRACT

We review the important properties of active nuclei, in particular (i) the optical polarization and its relation to the jets found by VLBI (ii) the energy distribution and the temporal variations of the continuum spectrum and (iii) the distribution of the matter in the broad line region.

I. INTRODUCTION

The highest angular resolution which can be achieved with the existing large ground based telescopes is obtained by speckle interferometry and corresponds to the diffraction limit of the telescopes: 2×10^{-2} arc sec for telescopes of 5m diameter. This technique has yielded results on relatively bright objects ($m_V < 18$) of simple structure. With the Space Telescope it is expected that a similar resolution will be obtained by deconvolution of direct images. Thus the best angular resolution achievable now or in the near future in the optical/UV range is coarser than the 10^{-3} arc sec currently achieved with radio VLBI. It is however possible to obtain important information on the linear dimensions of the most compact components of the sources emitting the optical/UV radiation from the time scale of their temporal variations and through theoretical arguments.

The components of active nuclei which have dimensions comparable to or smaller than the VLBI jets are the sources of optical and X-ray radiations, and the broad emission line regions. As for the broad UV absorption lines observed in some quasars and Seyfert galaxies, it can be shown that they are formed by clouds which cover a large fraction of the broad emission line region as viewed from the observer and which are outside the broad line regions. The absorbing region is thus much larger than the VLBI jets and for this reason it is not discussed here.

In NGC 4151 the linear dimensions of the UV continuum source and of

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TABLE 1

Sources with VLBI maps and measured Optical Polarization

Source Name	VLBI	Optical Polarization p%	Optical Polarization P.A.	Ref. - VLBI - Optical Polarization
3C 84	10°	1-6	usually in the range 100-160°	Pearson and Readhead, 1981 A.S. 1980
3C 371	83°	0-12	65° to 100°	Pearson and Readhead, 1981 A.S., 1980
3C 273	63°	0.2	52°	Readhead et al., 1979 Stockman et al., 1979
3C 345	101°	3.6	10° to 173° but preferred angle 80°	Unwin et al., 1983 Stockman et al., 1979 Impey et al. 1982
CTA 102	146°	1-11	100-170	Pearson et al., 1980 A.S., 1980
3C 390.3	139°	1-4	149-165	Linfield, 1981 A.S., 1980 Martin et al., 1983
3C 120	63°	0.9-1.2	99-103	Readhead et al., 1979 A.S., 1980 Martin et al., 1983
BL Lac	10°	2-23	0-180, no preferred angle	Kellermann et al., 1977 Pearson and Readhead, 1981 A.S., 1980 Puschell and Stein, 1980 Moore et al., 1982
3C 454.3	130°	0-16	0-170, no preferred angle	Pearson et al., 1980 A.S., 1980
0235+164	21±21	6-25	15-175, no preferred angle	Bååth et al., 1981 Impey et al., 1982
0735+178	45±13	3-31	0-175, no preferred angle	Bååth et al., 1981 Impey et al., 1982

Footnote to Table 1:

The values of the preferred angles (Angel and Stockman, 1980 - referred to above as A.S. 1980) are provisional and could be found to be different or even non-existent with further monitoring.

the broad emission line region as obtained from the observations of the temporal variations are of the order of 0.25 and 0.5 light-months respectively. At the distance of NGC 4151, ~15 Mpc, this corresponds to an angular dimension of approximately 10^{-4} arc sec. Note that if one makes the not unreasonable assumption that in first approximation the characteristic linear dimension of the broad line region of an active nucleus or quasar scales with $L^{1/2}$ (where L is the absolute luminosity of the UV central component), then all the active objects of comparable apparent luminosities have broad line regions of comparable angular dimensions.

II. POLARIZATION PROPERTIES

A) The Highly Polarized Objects

Among the seven compact radio sources where superluminal velocities have been observed (Cohen and Unwin, 1982) three have large and highly variable optical polarization which suggests a relationship between the two phenomena. The variations of the polarization in percentage and angle occur on time scales of days, i.e., much shorter than the variations occurring in the radio structure observed with VLBI. The variable optical polarization may come from a region which is smaller than the VLBI jet, perhaps the base of the relativistic jet. It must be noted that the relationship between highly variable optical polarization and superluminal sources is not a simple one since there are superluminal sources such as 3C 273, where the optical polarization is very weak, 0.2%. Table 1 gives the optical polarization properties of the radio sources which show jets on the VLBI scale and for which VLBI maps were published in June 1983. The table shows that when the optical polarization angle covers a relatively small range of position angle ($\lesssim 45°$) then <u>the direction of the VLBI jet falls in this range</u>.

In BL Lacertae, which has been studied extensively, the spectrum of the time variations of the optical polarization angle and of the total optical flux is consistent with a random walk spectrum (Moore et al., 1982). In some BL Lac objects and highly polarized QSOs there is transient evidence for wavelength dependent polarization (with the percentage polarization increasing with decreasing wavelength) while at other times and in other QSOs the polarization is wavelength independent (Bailey, Hough and Axon, 1983; Impey et al., 1982; Puschell et al., 1983). A simple - but not unique - model fitting all these observations is one in which the energy is emitted by a small number of independent sources (Moore et al., 1982), each emitting a fully polarized (70%) synchrotron radiation of random orientation and varying on a time scale of a few days. The "independent sources" could be inhomogeneities or sub-units in a beamed jet. In this model, the dependence of polarization on wavelength is easily explained if the spectral domains of the sources are different, as would happen if the spectral domains were limited by different amounts of radiative energy losses. The polarization properties are also consistent with non-uniform Faraday effect, and

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since electron radiative lifetimes are probably very short, there must be a large number of non-relativistic electrons (Puschell et al., 1983).

A satisfactory model must also be able to account for extreme variations such as the occasional large outbursts where the total energy increases by a factor up to 100 (Rieke et al., 1976; Moore et al., 1982) and the polarization outbursts like the one which occurred in 0235+164 during which the polarization reached 43% without much change in total flux (Impey, Brand and Tapia, 1982). Moore et al. (1982) speculate that the extreme total flux outbursts might be caused by an increase in the average luminosity of the components. Regarding the polarization outbursts, Impey et al. (1982) argue that these changes are caused by a large scale physical reordering of the magnetic field. Alternatively, if the emitting material is beamed towards us, then aberration exaggerates the effects, and small changes in the source geometry are amplified by relativistic effects and cause the observed large changes in flux, in percentage polarization, and in angle of polarization.

B) Seyfert Galaxies and Weakly Polarized Quasars

In the majority of quasars (20 out of 24 in the sample of Stockman, Angel and Miley, 1979) and of Seyfert 1 galaxies (5 out of 5 in the list of Antonucci, 1982) the optical polarization angle is rather well aligned with the angle of the associated radio structure on the VLA scale, i.e. the difference between the two angles, $\Delta\Theta$, is less than $\sim 20^\circ$. In the objects with $\Delta\Theta \sim 0^\circ$ the polarization could be intrinsic to the radiation mechanism. The fact that in NGC 4151 neither the broad nor the narrow emission lines have the same polarization as the continuum (Schmidt and Miller, 1980) strongly suggests that this is the case in at least some objects. More abundant data on spectral polarization and time variations should clarify this point. It must be pointed out that the discovery of variability of the angle of polarization in Seyfert 1 galaxies, e.g. NGC 4151, would be the best proof that some of the continuum is of synchrotron origin.

In Seyfert 2 galaxies and in Broad Line Radio Galaxies (BLRG) the percentage polarization can be very large and furthermore in many of these objects $\Delta\Theta$ is close to 90°.

It has been suggested that in Seyfert 2 galaxies and in BLRG the polarization is produced by scattering with, in some cases, intrinsic polarization of the continuum contributing to the total polarization. Rudy et al. (1983) argue that in BLRG, the polarization is due to scattering by dust because they find a correlation between the percentage polarization and the value of the Balmer decrements of the broad emission lines while Antonucci (1983) proposes that polarization is caused by electron scattering, with $\Delta\Theta \sim 90^\circ$ being produced by a thick scattering disk, and $\Delta\Theta \sim 0^\circ$ by a thin scattering disk.

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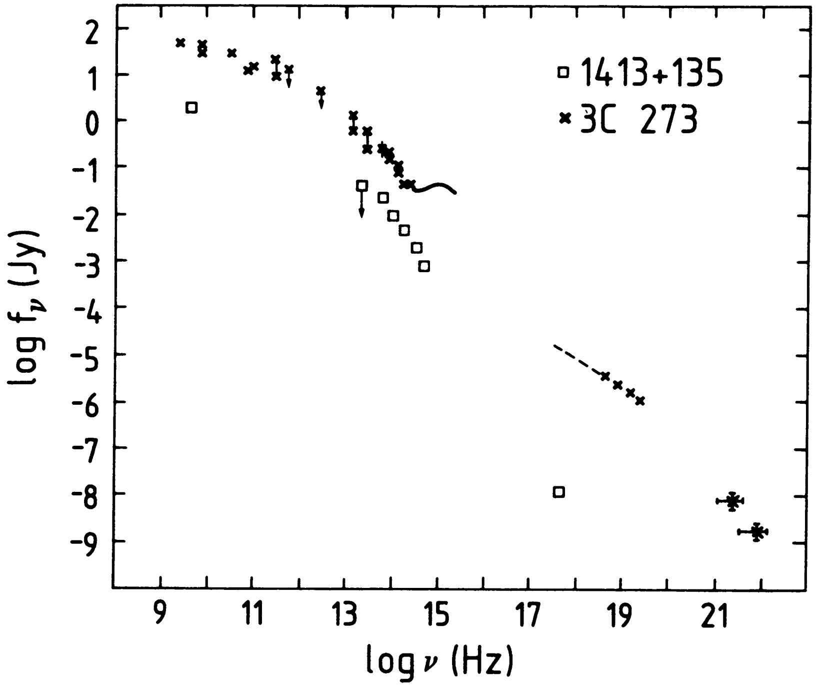

Figure 1. The electromagnetic spectrum of the quasar 3C 273 (Ulrich et al. 1980) and of the red object 1413+135 which is believed to be a BL Lac object (Bregman et al., 1981). Note the 3000 Å bump in the spectrum of 3C 273. This bump almost always occurs in conjunction with broad emission lines and is thought to be emitted in part by a ~ 30000°K accretion disk. In contrast, the spectra of BL Lac objects show a downward bend between 10^{14} and 10^{15} hz; this bend is particularly strong in 1413+135.

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III. THE CONTINUUM SPECTRUM

A characteristic feature of the optical/UV continuum spectrum of quasars and Seyfert 1 galaxies is the presence of an excess of radiation in the range 3000 - 4000 Å over the extrapolation of the power law which represents the spectrum between 10μ and 5000 Å. (Figure 1). This excess, "the 3000 Å bump", seems always to be present in the spectrum in conjunction with broad emission lines and is generally believed to be a combination of black body radiation, optically thick Balmer continuum, 2-photon continuum, and blends of Fe II lines (Baldwin, 1977; Grandi, 1982; Malkan and Sargent, 1982).

In contrast the IR/optical/UV spectrum of BL Lac objects steepens between 10^{14} and 10^{15} hz, the exact frequency of the bend depending on the object (Maraschi, Tanzi and Treves, 1983). A similar bend might be present in the spectrum of Seyfert galaxies but remain undetected because of the 3000 Å bump.

It is not clear, at least to the reviewer, whether there is a difference between the nonthermal radiation of BL Lac objects and the nonthermal radiation of quasars and Seyfert galaxies. The IR/optical/UV spectrum of the latter could be nonthermal radiation as in BL Lac objects to which is added re-emission by dust in the IR and the 3000 Å bump in the optical/UV range.

Seyfert galaxies and BL Lac objects differ also by the temporal variations of their UV spectrum. In Seyfert galaxies the UV spectrum becomes harder when the object brightens (e.g. Perola et al., 1982; Boisson and Ulrich, 1982) while in the BL Lac object Mrk 421 (Figure 2) and in intrinsically bright BL Lac objects there is no correlation between spectral slope and intensity (Ulrich et al., 1984). The difference in temporal behavior between the UV continuum of Seyfert galaxies and BL Lac objects could be due to real differences in the properties of the non-thermal continuum related to differences in the accretion regime in Seyfert nuclei and in BL Lac objects (e.g. Maraschi, Perola and Treves, 1980). On the other hand, the correlation observed in Seyfert galaxies may result from the variations of the different components of the continuum.

IV. THE BROAD EMISSION LINE REGION

The broad emission line region is formed by many dense gas clouds distributed in the region with a very small filling factor. Some basic properties of the broad emission line gas in quasars and Seyfert galaxies have been known for nearly a decade and others are being explored. They are reviewed below in order of decreasing certainty.

(i) The particle density is in the range 10^9-10^{11} cm^{-3}. The line width is ~ 10^4 km s^{-1} and caused by gas motions. The degree of ionization and the particle density in the gas clouds are similar in objects differing

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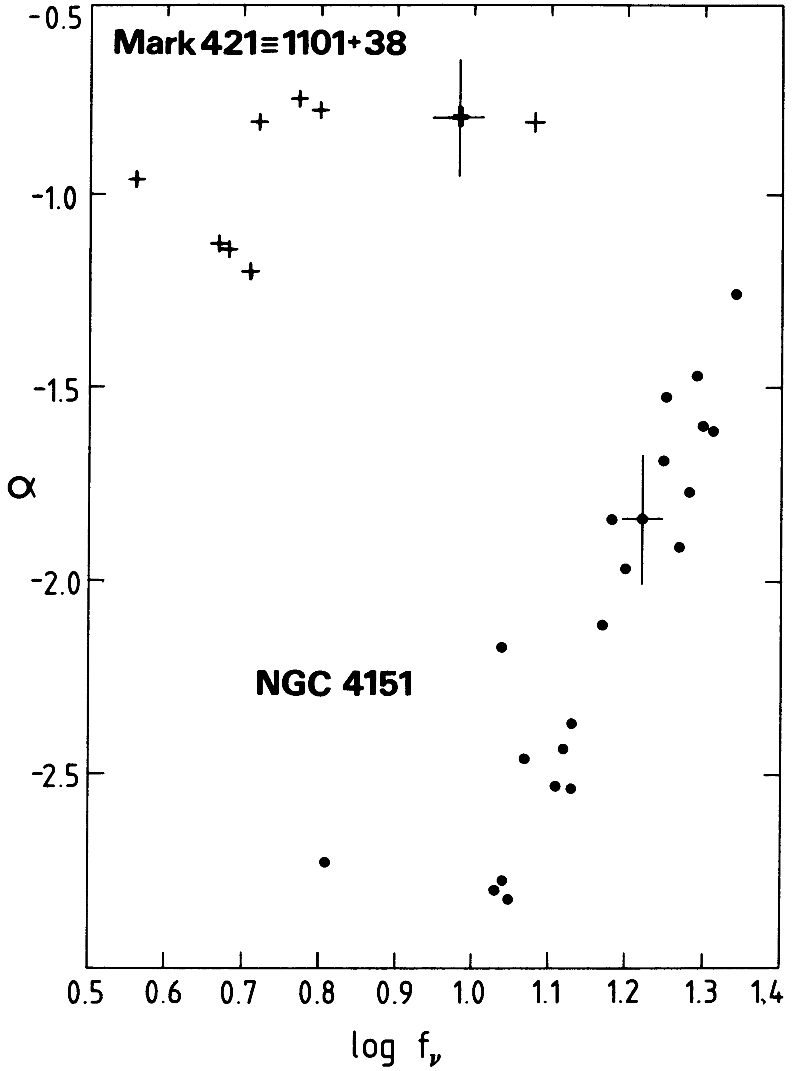

Figure 2. The spectral index, α, plotted as a function of the flux level at 2500 Å in NGC 4151 (Perola et al. 1982) and in Mrk 421 (Ulrich et al. 1984). In NGC 4151 the spectral index was measured between 2000 and 3000 Å. The measurements plotted here come from 21 different epochs of observations. In Mrk 421 the spectral index was measured between 1300 and 3000 Å at 9 epochs. In NGC 4151, and in other Seyfert galaxies, there is a strong correlation between α and log f_ν at 2500 Å. No such correlation has yet been detected in Mrk 421 nor in intrinsically bright BL Lac ojbects. Two typical error bars are marked.

by 10^4 in absolute luminosity; this suggests that the linear dimension of the broad line region must be roughly proportional to the square root of the UV continuum luminosity. In quasars similar to 3C 273 in luminosity the linear dimension of the broad line region is ~ 1 to 5 pc i.e. comparable to the dimension of the VLBI jet. In NGC 4151, it is approximately 5×10^{16} cm.

(ii) More recently it has become clear that the large Hβ/Lyα intensity ratio observed in the spectra of quasars and Seyfert galaxies is due to collisional enhancement of Hβ and implies a very large optical depth. In such conditions the clouds emitting the bulk of Hβ must emit the Lyα line in a very anisotropic way which imposes strong constraints on models for the broad line region. Also it has been realized that the column density in each cloud is $< 10^{23}$ cm^{-2}, otherwise the intensity of CII]λ2326 would be larger than observed (Kwan and Krolik, 1981). This, together with the high value of n_e, indicates a very small linear dimension for the cloud, ~ 10^{13} cm, at least in the direction to the continuum source.

(iii) In the last two years, it has been recognized that the analysis of the variations of the emission line intensity and profile could give information on the structure of the broad line region. In the case of NGC 4151 which is the best studied object, this analysis leads to a model for the broad line region in which the velocity of the clouds, their optical thickness and their distance from the central continuum source are correlated, the clouds having the largest velocities and smallest optical thickness being closer to the continuum source (Ulrich et al., 1983; Ulrich, 1983). The mass of the central object deduced from the line width and variability time-scales is 0.5 to 1.0 × 10^8 $M_\odot$. The size of a 30000°K accretion disc surrounding a black hole of this mass (Lynden-Bell, 1969) is consistent (perhaps by mere coincidence) with the excess of radiation observed at 1455 Å over the power law component fitting the rest of the UV/optical spectrum (Ulrich et al., 1983).

(iv) Recently several arguments have been put forward suggesting that the broad line region in quasars and Seyfert galaxies is made up of two types of clouds differing by their physical conditions and also by their location with respect to the central continuum source:

- The high degree of symmetry of Lyα and the similarity of the Lyα and CIV profiles in the few well studied high redshift quasars (Wilkes and Carswell, 1982) indicate that most of Lyα and CIV is likely to come from small optically thin clouds emitting isotropically.

- The lack of correlation in Seyfert galaxies between the variations of Lyα and the variations of MgII λ2800 suggests that MgII, which is emitted by optically thick, partially ionized gas, does not come from the same clouds which emit the bulk of Lyα (in preparation).

- The extreme difficulty in reproducing in one type of clouds the observed line intensity ratios when the transfer is properly treated

(Collin-Souffrin, Dumont and Tully, 1980) is a strong argument in favor of two types of clouds.

These arguments lead to models of the broad line regions where most of Lyα and CIV is emitted by small optically thin clouds distributed more or less spherically around the central continuum source. As for the optically thick clouds emitting the Balmer lines and the FeII and MgII lines, Gordon, Collin-Souffrin and Dultin-Halcyan (1981) suggest that they could be mechanically heated and possibly form the outer part of an accretion disk, while Norman and Miley (1983) propose that the optically thick clouds could form the cocoon of a relativistic radio jet.

(v) The broad line clouds are so small (10^{13} cm in at least one dimension) that if they are not constrained by some external pressure their linear dimension doubles in a time much shorter than the crossing time of the broad line region. There must therefore exist an <u>intercloud medium</u> exercising a high thermal pressure, without causing a strong drag which would prevent the acceleration of the clouds at the observed high velocities. A mildly relativistic medium at $T > 10^8$ °K would fulfil these requirements and Weymann et al. (1982) have recently discussed the properties of such a medium. Alternatively, the broad line clouds could be instabilities in a cold medium (M. Begelman, this Volume).

Finally, a review article should not end without a list of as yet unanswered questions:

- What is the nature of the IR/optical/UV continuum in Seyfert galaxies and quasars? Is there a difference between the non-thermal continuum of BL Lac objects and that of other objects, a difference which would be related to differences in the accretion regimes?

- Is there circulation of gas in and out of the central region with some gas being accreted and a fraction of it being ejected by mechanical or radiation pressure?

- What is the nature of the very dense gas clouds? Are they formed as such by evaporation from a disk or star disruption or are they cool condensations in a hot medium?

- Is the 30000 Å bump caused by black body radiation from an accretion disk, and how are the dense gas clouds related to this disk?

- What is the role of dust in changing the apparent shape of the spectrum in the infrared, optical and UV ranges, as well as in changing the line intensities?

- Why is there no dense gas observed in BL Lac objects?

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