OPTICAL SPECTRUM VARIABILITY OF SEYFERT GALAXY NUCLEI

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I. INTRODUCTION

In this contribution I will present some results of a program aimed at determining the optical variability characteristics of Seyfert galaxy nuclei. It has been known for more than a decade that the continuous, non-stellar light of Seyfert nuclei can vary significantly on a time scale of months to years (see, e.g., Lyutyi, 1973, 1977; Penston et al., 1974; Penfold, 1979). In recent years there also have been various reports of variations in the intensity of the broad optical emission lines (Boksenberg and Netzer, 1977; Tohline and Osterbrock, 1976) following the pioneering work by Souffrin et al. (1973) and Cherepashchuk and Lyutyi (1973). However, very little is known on the details of the continuum variations and how they relate to the line variability. Such information could provide valuable constraints on the fashionable photoionization models for the broad line region (BLR) and the structure of the latter.

The observations used in the present investigation were obtained with Oke's multi-channel spectrophotometer (MCSP) on the Hale 5-meter telescope over the period 1974-1978. The 1974/1975 scans were taken by Sargent. Most of the early scans have already been published as part of an extensive spectrophotometric study of a large number Seyfert galaxies (de Bruyn and Sargent, 1978) to which I refer for more information about the operation of the MCSP and the calibration and reduction of MCSP scans.

For a total of 15 objects we have more than one scan up to a maximum of five for one object (NGC 7469). The photometric accuracy of the individual scans is about $0^{m}.05$. This accuracy could be obtained by using a 10" aperture for all scans. The penalty for using such a large aperture is that the spectra will be contaminated by a non-negligible amount of background starlight. This non-variable radiation will dilute the variations that we are interested in.

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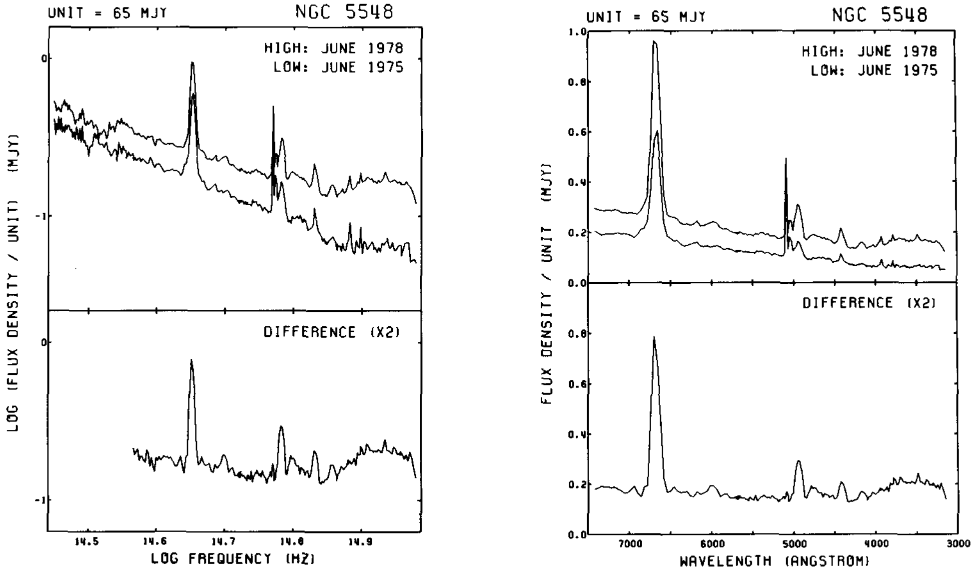

Fig. 1. Spectral scans of the Seyfert galaxy NGC 5548 taken with the MCSP on dates three years apart. Both logarithmic (left) and linear (right) versions of the data are shown. The top part of each figure shows the individual scans; the bottom part shows the difference spectrum. (See text).

In §2 I will present a selection of the results that were obtained, while §3 contains a discussion of the most interesting implications. Finally, in §4 the statistical results for the whole sample of 15 objects will be presented. A more extensive account of the data and their interpretation will be given elsewhere (de Bruyn, 1980).

2. RESULTS

In the upper part of Figure 1 are shown two spectral scans of the Type 1 Seyfert galaxy NGC 5548 taken in 1975 and 1978. The logarithmic version of the data, shown left, covers the wavelength range from 3150 Å to 10660 Å in 270 wavelength bands. The bands are 20 Å wide in the blue and 40 Å wide in the red part of the spectrum; the change occurs around 5700 Å. The same data are represented on linear scales on the right side but have been truncated at 7420 Å. The bottom parts of Figure 1 show the difference spectra multiplied by a suitable factor. Note that all spectra have been normalized on the same unit value given at the top of the figure, and do not have displaced zero levels (1 mJy = 10^{-26} erg s^{-1} cm^{-2} Hz^{-1}). A spectrum of NGC 5548 taken in 1974 (de Bruyn and Sargent, 1978) showed the source to be at an intermediate level.

To convince oneself of the reality of the features seen in the difference spectrum it suffices to look at the residuals of the strong

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narrow forbidden lines of [OIII] at 4959 and 5007 Å. This absence of variability in the narrow forbidden lines is consistent with our thinking on the structure of Seyfert nuclei, where these lines come from a much larger region than the broad lines, and are therefore not expected to vary on such a short timescale. The [OIII] lines in NGC 5548 cancelled to within 5%. In fact, for the 28 difference scans accumulated in this program I find an rms difference for the intensity of the [OIII] pair in individual scans of the same object of about 7%. The Balmer lines, on the other hand, varied dramatically, with H_α increasing by 65% and H_β by 120%. I will return to the line variability in §3.2.

An equally interesting aspect of the difference spectrum is the fact that its continuum slope is considerably flatter than that of the individual spectra. This is already evident from a comparison of the 1975 and 1978 spectra as plotted in logarithmic form. The vertical distance between the scans at a certain wavelength is a direct measure of the change in magnitude at that wavelength. This shows directly why in UBV-variability studies the largest variation is always measured in the U-filter.

A third conspicuous feature in the difference spectrum is the strength of the well-known blue-violet bump, first measured in detail by Oke and Sargent (1968) in NGC 4151. It sets in at about 4100 Å rest wavelength and reaches a flat plateau around 3600 Å. However, if we take into account the emission from the confluence of higher order Balmer lines, the blue-violet bump begins at around 3700-3800 Å rest wavelength and also increases in intensity more abruptly. It seems attractive to identify this bump with the Balmer continuum coming from the same gas that produces the variable Balmer line emission. However, on the basis of the observed H_α - variation we expect the Balmer continuum intensity in the variable spectrum to be only about 1/3 to 1/4 of what is actually observed. This discrepancy between the observed bump strength and the predicted Balmer continuum intensity applies to all objects in which we witnessed a significant variation. The discrepancy does, however, vary from a factor 2 to 20 among the objects. The bump is also conspicuous in the spectra of low-redshift QSO's (Baldwin, 1975; 1977a; Neugebauer et al., 1979) where its strength presents similar problems.

If we exclude the region of the blue-violet bump the continuous spectrum of the variable emission in NGC 5548 can be fitted by a power-law of index $\alpha \approx -0.5$ ($f_\nu \propto \nu^\alpha$). The 1975 and 1978 total spectra had indices of -2.0 and -1.4, respectively, over the same wavelength region. These values refer to the observed spectra; a correction for galactic extinction of $A_V = 0^m.25$ would increase α by about 0.3.

In Figure 2 are shown two spectra, and their difference, for both NGC 3516 and Markarian 205. Between 1977 and 1978 NGC 3516 became fainter by more than $0^m.8$ in the violet. When compared to the 1974 spectrum, the total decrease has been more than $1^m.0$ in the U-band. The 1975 spectrum, published by de Bruyn and Sargent (1978), was identical to

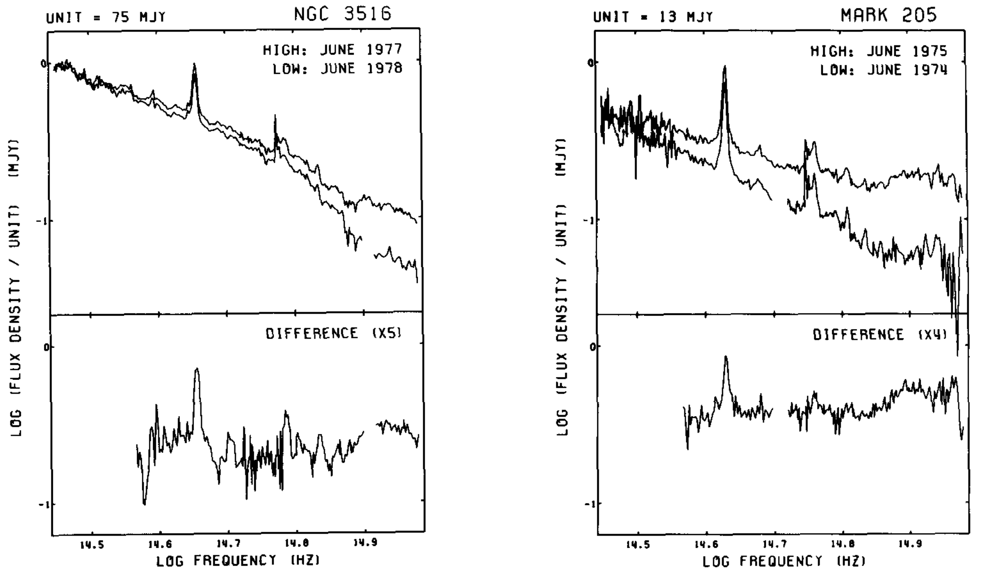

Fig. 2. Spectral scans of the Seyfert galaxies NGC 3516 and Markarian 205. Only the logarithmic version of the data is shown. (For more details see the text).

the 1977 spectrum to within the errors. Mark 205 underwent a large outburst between 1974 and 1975, whereby its U-magnitude decreased by about $1^{m}.30$. In June 1978 the object was measured to be at an intermediate level.

The NGC 3516 and Mark 205 difference spectra are qualitatively rather similar to that of NGC 5548. Their blue-violet bumps are, however, more pronounced, relative to the variable H_{α}-emission, than in NGC 5548. Note also the very flat slopes of the variable continua which, when corrected for $A_v = 0^{m}.20$ galactic extinction, have power-law indices of $\alpha = +0.20$ (Mark 205) and $\alpha = -0.05$ (NGC 3516).

3. DISCUSSION

3.1 The Nature of the Continuous Spectrum

One of the most outstanding characteristics of Seyfert galaxies is the intense featureless optical continuum. It is generally believed that this continuum has a non-thermal origin and rises fairly steeply ($\alpha \approx -1.25$) into the infrared to become the dominant radiation component there (Stein and Weedman, 1976; Neugebauer et al., 1976). The results of the previous section suggest a more complicated picture wherein the featureless continuum has a considerably flatter spectral slope, at least in the blue part of the spectrum ($\lambda \lesssim 6000$ Å). A considerable fraction of the light in the near-infrared region (7000-10000 Å) also must be due to background starlight, hence it is not clear whether we require the presence of an additional continuum component with $\alpha \approx -1.25$ to explain the overall spectrum (see also Rieke, 1978). In any case, whatever the strength of this component, it does not appear to contribute to the optical variability. The lack of well-documented infrared variability in Seyfert galaxies (Rieke, 1978) could thus be explained if the variable continuum maintains its flat spectral slope well into the infrared.

A more fundamental question concerns the radiative origin of the variable continuum. Although the belief that the continuum is of non-thermal origin is apparently widespread, there is no convincing evidence in support of this assumption. On the contrary, I suggest - following a suggestion by Shields (1978) - that the flat continuum is the thermal 'black body' emission from an optically thick accretion disk. The observed spectrum has about the right slope for an accretion disk spectrum (Shakura and Sunyaev, 1972). The lack of optical polarization in most Seyferts and QSO's (Stockman and Angel, 1978; Thompson et al., 1979) is consistent with a thermal origin of the continuum. The strongly polarized and rapidly variable continua observed in BL Lac type objects distinguish themselves from the flat variable continua in Seyfert galaxies by their much steeper power-law spectra. Perhaps such components are also present in Seyfert galaxies but at a very low level of activity.

Within the framework of the accreting disk model it may also be possible to explain the blue-violet bump, which is so strong in the difference spectra. Shields (1978) has suggested that this bump is indeed the Balmer continuum emission, but is coming from the inner part of the disk provided it has a temperature inversion. The line emission expected from this region is much less than that from the broad line region due to limitations imposed by the size (10^{15} - 10^{16} cm) and temperature ($\sim$ 20000 K) (see Rees, 1977).

3.2 A Detailed Look at the Line Variability

A cursory inspection of the 1975 and 1978 spectra of NGC 5548 (right side of Fig. 1) reveals that the higher order Balmer lines have an increased strength, relative to H_α, in the high intensity spectrum. The same is true for NGC 3516 and several other galaxies in the program not discussed here. In a galaxy like NGC 3516, however, the relative line variations are more difficult to determine because of the bumpy underlying continuum caused by galaxian absorption features. In fact, neither in the low nor in the high intensity NGC 3516 spectrum (Fig. 2) is there clear evidence for the presence of H_δ, although the difference spectrum shows definite H_δ variability.

To investigate the relation between the continuum intensity and the Balmer decrement, five spectra of NGC 7469, acquired over a period of four years, were analysed in detail. The results are shown in Figure

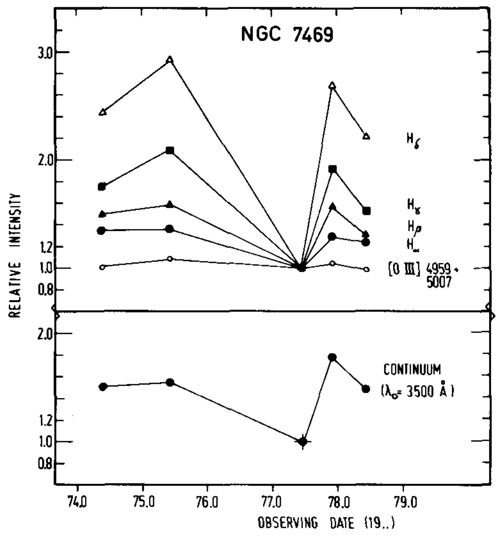

Fig. 3. A detailed look at the relative variations of the 3500 Å continuum and the Balmer lines in the Seyfert galaxy NGC 7469 over a period of 4 years. The intensities of the lines and continuum have been normalized on their values in June 1977 when they were at an intensity minimum.

3. The H_α line intensity has been corrected for the (non-variable) contribution of the [NII] 6548, 6583 Å doublet; similarly, H_γ was corrected for the contamination by the [OIII] 4363 Å line. When both the continuum and the lines were at an intensity low in June 1977, the Balmer decrement was 4.20/1.00/0.43/0.18 ($H_\alpha/H_\beta/H_\gamma/H_\delta$) which is significantly steeper than that of an unreddened case B decrement (Osterbrock, 1974). In June 1975 and December 1977, however, the Balmer decrement was very different, and in fact closer to 'normal'. The Balmer decrement variation is inconsistent with a change in the amount of reddening, as both the H_α/H_β and H_δ/H_β ratio are larger in June '75 and December '77 than their respective case B values. Variations in the H_α/H_β ratio in Seyfert galaxies have previously been observed by Tohline and Osterbrock (1976) and Boksenberg and Netzer (1977) among others. The latter authors also suggest a possible explanation for such variations, which is based on changes in the optical depth in H_α (see Netzer, 1975; 1977).

4. STATISTICAL BEHAVIOUR

In this section I will describe some results for the whole sample of objects, and discuss a general characteristic of the variability behaviour. For the 15 objects we collected a total of 43 spectrum scans. For each of these I determined the luminosity of the H_α emission line

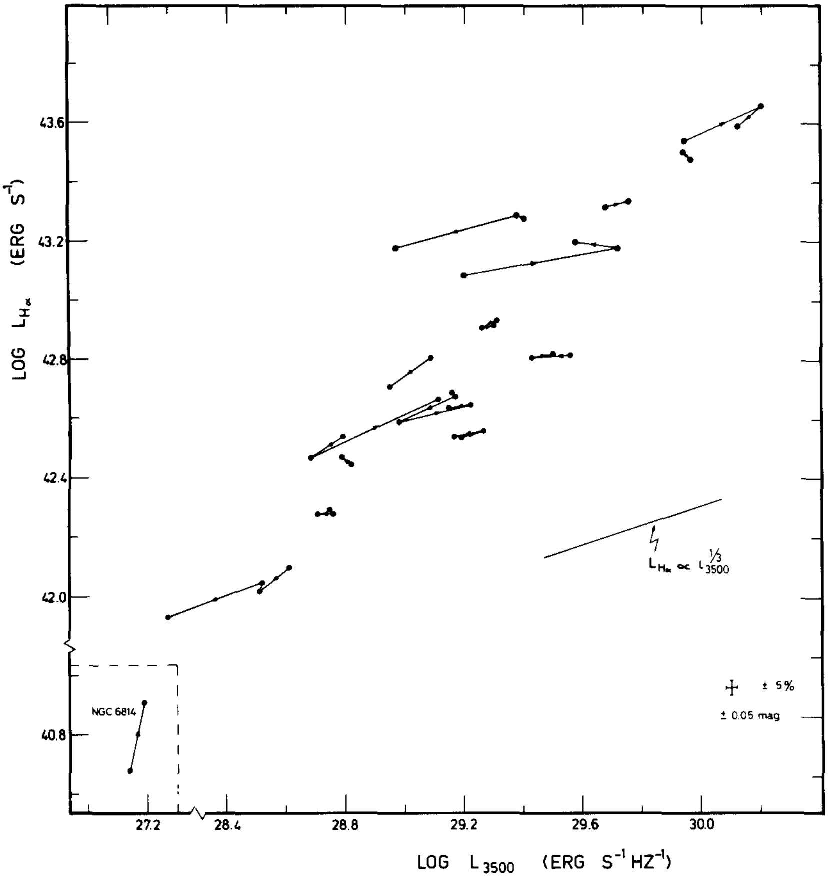

Fig. 4. Plot of the H_α luminosity against the 3500 Å continuum luminosity for all 15 objects in the sample, including those for which we believe there is no evidence for variability. A typical error cross for each of the 43 observations entered in this diagram is shown in the bottom-right corner. For reference purposes a line with slope +1/3 is also shown.

and that of the continuum at 3500 Å restwavelength. The results are shown in Figure 4. Data points for the same object have been connected by straight lines with the observing date increasing as shown by the arrowheads. A typical time interval between chronologically successive scans is about one year.

The concentration of objects in a narrow strip inclined at about 45° to the axis is partly due to observational selection; the objects with the highest luminosities also tend to be the furthest (Malmquist bias). The interesting point, however, about Figure 4 is that for nearly all cases of significant variability the H_α and continuum intensity variations are positively correlated, independent of the sense of the

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observed variation. A physical model that could explain such a correlation involves the photoionization of the gas by the ultra-violet extension of the variable optical continuum. However, since the broad line region has a finite size the dominant continuum variations must occur on a time scale that matches the light-travel-time across the broad line region. If the continuum were to vary on a much shorter timescale than the latter, without a slower larger amplitude variation as well, the gas would show a delayed, and reduced, response which should result in uncorrelated instantaneous line and continuum fluxes.

An intriguing result is the fact that the H_α - luminosity varies, on average, as approximately the + 1/3 power of the continuum luminosity. This + 1/3 dependence implies that the broad line region is intermediate between a density-bounded and ionization-limited HII region. Only NGC 6814 deviates strongly in this respect. It is one of the intrinsically faintest Seyfert nuclei and the 3500 Å continuum flux in the 10" aperture probably contains a significant, if not dominant, non-variable stellar contribution. This component would dilute any non-stellar continuum variation, leading to a much steeper slope in Figure 4.

We obtain an interesting but puzzling result when we express the H_α line intensity in terms of the strength of the 3500 Å continuum. We then find that, on average, the "equivalent width" of H_α is about proportional to the - 2/3 power of the continuum luminosity: $W_{3500}\ (H_\alpha) \propto L_{3500}^{-2/3}$. This is the same proportionality as found by Baldwin (1977b) between the equivalent width of the CIV resonance line at 1549 Å and the 1450 Å continuum luminosity. That is to say, within individual Seyfert galaxies the line and continuum intensity appear to vary according to a relation that links similar quantities in an ensemble of quasi-stellar objects. The importance of this result is unclear. As the results of section 3.2 indicate we would obtain quite a different proportionality if we were to correlate, e.g. the H_β equivalent width with the continuum luminosity.

REFERENCES

Baldwin, J.A.: 1975, Astrophys. J. 201, 26.
Baldwin, J.A.: 1977a, Mon.Not.R.Astron.Soc. 178, 67P.
Baldwin, J.A.: 1977b, Astrophys. J. 214, 679.
Boksenberg, A., and Netzer, H.: 1977, Astrophys.J.212, 37.
De Bruyn, A.G.: 1980 (Submitted to Astrophys. J.).
De Bruyn, A.G. and Sargent, W.L.W.: 1978, Astron.J. 83, 1257.
Cherepashchuk, A.M., and Lyutyi, V.M.: 1973, Astrophys. Lett. 13, 165.
Collin-Souffrin, S., Alloin, D., and Andrillat, Y.: 1973, Astron. Astrophys. 22, 343.
Lyutyi, V.M.: 1973, Soviet Astr. AJ 16, 763.
Lyutyi, V.M.: 1977, Soviet Astr. AJ 21, 655.
Netzer, H.: 1975, Mon.Not.R.Astron.Soc. 178, 489.
Neugebauer, G., Becklin, E.E., Oke, J.B., and Searle, L.: 1976, Astrophys. J. 205, 29.

https://doi.org/10.1017/S1539299600004524 Published online by Cambridge University Press

Neugebauer, G., Oke, J.B., Becklin, E.E., and Mathews, K.: 1979, Astrophys. J. 230, 79.
Oke, J.B., and Sargent, W.L.W.: 1968, Astrophys. J. 151, 807.
Osterbrock, D.E.: 1974, in "Astrophysics of Gaseous Nebulae", W.H. Freeman and Co., San Fransisco.
Penfold, J.E.: 1979, Mon.Not.R.Astron.Soc. 186, 297.
Penston, M.V., Penston, M.J., Selmes, R.A., Becklin, E.E., and Neugebauer, G.: 1974, Mon.Not.R.Astron.Soc. 169. 357.
Rees, M.: 1977, Ann. N.Y. Acad. Sc. , 613.
Rieke, G.H.: 1978, Astrophys. J. 226, 550.
Shakura, N., and Sunyaev, R.: 1972, Astron. Astrophys. 24, 337.
Shields, G.A.: 1978, Nature, 272, 706.
Stein, W.A., and Weedman, D.W.: 1976, Astrophys. J. 205, 44.
Stockman, H.S., and Angel, J.R.P.: 1978, Astrophys. J. 220, L67.
Thompson, I., Landstreet, J.D., Angel, J.R.P., Stockman, H.S., Woolf, N.J., Martin, P.G., Maza, J., and Beaver, E.A.: 1979, Astrophys. J. 229, 909.
Tohline, J.E., and Osterbrock, D.E.: 1976, Astrophys. J. 210, L17.