

Optical variability of Seyfert nuclei

II. Fairall 9[★]

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Abstract. The Seyfert galaxy Fairall 9 has been observed photometrically as well as spectroscopically over a period of ten years. The strength of both the continuum and the broad emission lines has varied considerably, but, in contrast to many other Seyfert galaxies, in a very regular and gradual way.

It is shown that the data of the Walraven photometry can be used to calibrate the spectra to an accuracy of $\sim 5\%$.

According to the continuum light curves the brightness of Fairall 9 continually decreased from 1979 till the end of 1984, and from 1988 till the end of 1989. A phase of brightening, lasting from 1984 till 1987, interrupted this general dimming. The brightness at the time of the discovery of Fairall 9 (around 1977) has never been reached again in the following 12 years.

Using also UV continuum and line data available in the literature, it is shown that the continuum, from optical to UV wavelengths, varies simultaneously, while both the UV and the optical spectral index remained constant over the time interval 1979–1989. However, the ratio of UV to optical flux varied drastically (by a factor of ~ 5), probably because of the presence of a constant component that is only important in the optical.

The behaviour of the broad emission lines is very similar to that of the continuum, but in general they lag behind it, by an amount depending on the type of line considered. Several lines (e.g. H β , Ly α , C IV) are delayed by 7–9 months, while low excitation Fe II lines respond to the continuum changes only after more than 1–2 years. The different delays and their implications are discussed.

Key words: Seyfert galaxies – photometry – spectroscopy

1. Introduction

Optical variability of the nuclei of type 1 Seyfert galaxies has become an important object of study. Several Seyfert galaxies have been observed on a regular basis in the past decade, notably NGC 4151 (Antonucci & Cohen 1983; Ulrich et al. 1984; Clavel et al. 1987; Clavel et al. 1990) and NGC 5548 (Peterson 1987; Stirpe

et al. 1988; Netzer et al. 1990; Peterson et al. 1990; Wamsteker et al. 1990; Clavel et al. 1991; Peterson et al. 1991), but many more have been studied in less detail, e.g. Fairall 9 (Wamsteker et al. 1985; Kollatschny & Fricke 1985; Clavel et al. 1989; Stirpe et al. 1989), Akn 120 (Peterson et al. 1983; Peterson & Cota 1987; Alloin et al. 1988), 3C 120 (French & Miller 1980; Oke et al. 1980).

The monitoring campaigns have provided important results that are very helpful for gaining a better understanding of the broad-line region (BLR) in active galactic nuclei. First, it has been established beyond doubt that in addition to the optical continuum some of the broad emission lines vary in strength as well, although not necessarily by the same amount (De Bruyn 1980). The emission line changes appear to be proportional to the continuum (Peterson et al. 1985), but this is mostly due to the usually rather coarse time resolution of the lightcurves: the spectra are very often taken at least a few months apart. Intensive monitoring campaigns have revealed that many broad emission lines change out of phase with respect to the continuum, in the sense that they lag behind (Antonucci & Cohen 1983; Ulrich et al. 1984), although the magnitude of the delay may differ for different objects or even for different lines in the same object (De Bruyn 1980; Wilkes & Carswell 1982; Antonucci & Cohen 1983; Stirpe 1989). Clearly, the variability data contain information on the geometrical structure of the BLR since the delays are caused by light-travel time effects. Furthermore, line profile studies may in principle be used to determine the structure of the BLR (Blandford & McKee 1982; Van Groningen 1984; Stirpe 1989).

For several reasons Fairall 9 (ESO 113-IG45) is a highly interesting type 1 Seyfert galaxy. When it was discovered around 1977 (Fairall 1977; West 1977) its luminosity was that of an average quasar (Danks et al. 1979); because of its low redshift the underlying galaxy was clearly visible, which explains the classification of Fairall 9 as a (type 1) Seyfert galaxy. Since then the luminosity of Fairall 9 has undergone drastic, but rather regular changes: the object became fainter by almost exactly one magnitude in the visual (and more in the ultraviolet) between 1979 and 1984. After the minimum reached at the end of 1984 it became brighter again in the period 1984–1987, followed by a new decrease in the last three years. As shown in this paper, the regularity of the variability offers the opportunity to study delay effects even from widely sampled data.

The paper is organized as follows: first we present the photometric and spectroscopic data (Sect. 2) collected in ten years of observations at ESO (La Silla). We specifically discuss the

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[★] Based on observations collected at the European Southern Observatory, La Silla, Chile

calibration of the spectra with the help of the Walraven *VBLUW* photometry and show that very satisfactory results can be obtained. In Sect. 3 we present the light curves of the continuum and of several emission line ($H\beta$ and $H\alpha$) and discuss the different time delays found between the broad lines and the continuum.

2. The data

2.1. Walraven *VBLUW* photometry

Since 1979 we regularly follow a sample of Seyfert galaxies; in general once a year the programme objects are observed photometrically as well as spectroscopically. Basically the sample comprises the Seyfert galaxies known around 1979, which have a declination below $\sim 10^\circ$ and are therefore accessible to the telescopes of ESO (La Silla). In de Ruiter & Lub (1986) – hereafter Paper I – we presented the photometric data obtained in the period 1979–1982.

One object, Fairall 9, stood out because of its large and regular changes in brightness compared to the rest of the sample. For this reason we decided to dedicate a more detailed study to Fairall 9, based on the photometry and spectroscopy collected during the period 1979–1990. This study is presented here. We also continued observations of the other galaxies in the original sample of Paper I, but these will be discussed in a future article.

The photometry was done using the Walraven *VBLUW* photometer mounted on the Dutch 90 cm light collector at ESO, La Silla. A description of the Walraven photometric system was already given in Paper I, to which we refer for details. We only add that the parameters of the Walraven bands have been remeasured in 1987 (Pel, private communication); the newly determined effective wavelengths and bandwidths (in $\text{\AA}$) are: *V*: 5413, 707.5; *B*: 4262, 422.9; *L*: 3845, 221.1; *U*: 3614, 232.2; *W*: 3232, 156.5. The differences with the old values are relatively small, considering the required accuracy for an object like Fairall 9. The Walraven photometer (Walraven & Walraven 1960) has several advantages over the more commonly used photometric systems. First, it registers the five bands *simultaneously*, by way of an ingenious splitting of the relevant wavelength ranges, and this obviously saves a lot of observing time. Second, three of the bands (*L*, *U* and *W*) are in the range 3000 to 4000 $\text{\AA}$, which is of interest in particular for the study of Seyfert galaxies; the *W* band has an effective wavelength close to 3200 $\text{\AA}$, i.e. in a region not covered by conventional photometry. Third, the Walraven system uses an extensive set of standard stars (Lub & Pel 1977), which allows quite accurate photometric calibration (see Paper I for a general discussion on the accuracy of the photometry).

In Table 1 we list all individual *VBLUW* measurements done since the start of our monitoring programme, as usual given in

Table 1. *VBLUW* measurements

Date yyymmdd	Aperture (arcsec)	<i>V</i>	<i>V</i> – <i>B</i>	<i>B</i> – <i>L</i> ¹⁰ log (intensity)	<i>L</i> – <i>U</i>	<i>U</i> – <i>W</i>
791211	11.6	–2.647	0.131	–0.060	–0.048	0.030
791212		–2.632	0.140	–0.060	–0.051	0.028
791215		–2.648	0.130	–0.054	–0.064	0.023
791216		–2.635	0.133	–0.067:	–0.052	0.027
791220		–2.634	0.131	–0.063	–0.049	0.042
791221		–2.631	0.132	–0.068	–0.051	0.020
791222		–2.628	0.134	–0.057	–0.061	0.037
791224		–2.646	0.130	–0.069	–0.053	—
791225		–2.631	0.138	–0.065	–0.051	—
800806		–2.672	0.136	–0.067	–0.053	0.038
800807		–2.651	0.139	–0.070	–0.046	0.031
800809		–2.655	0.141	–0.076	–0.055	0.045
800811		–2.662	0.139	–0.070	–0.055	0.040
800812		–2.659	0.137	–0.067	–0.059	0.046
800813		–2.658	0.143	–0.078	–0.050	0.039
800817		–2.654	0.139	–0.074	–0.053	0.037
801214		–2.733	0.171	–0.062	–0.053	0.046
811120		–2.743	0.152	–0.058	–0.057	0.043
811121		–2.733	0.162	–0.061	–0.050	0.049
811201		–2.745	0.168	–0.057	–0.063	0.055
811202		–2.751	0.161	–0.054	–0.053	0.043
811203		–2.752	0.160	–0.052	–0.054	0.048
811227		–2.742	0.156	–0.057	–0.042	0.029
820103		–2.735	0.154	–0.053	–0.050	0.033
821207		–2.879	0.227	–0.038	–0.063	0.046
821219		–2.886	0.217	–0.029	–0.059	0.042
821220		–2.882	0.212	–0.018	–0.064	0.042
821221		–2.890	0.211	–0.025	–0.058	0.038
831208		–3.013	0.271	0.018	–0.046	0.019
831209		–2.990	0.275	0.038	–0.071	0.035
841223		–3.024	0.286	0.066	–0.039	0.017

Table 1 (continued)

Date yymmdd	Aperture (arcsec)	V	$V-B$	$B-L$ $^{10}\log(\text{intensity})$	$L-U$	$U-W$
841224		-3.026	0.283	0.060	-0.056	0.042
841226		-3.018	0.278	0.046	-0.040	0.050
841227		-3.019	0.281	0.049	-0.040	0.043
851210		-2.933	0.218	-0.006	-0.051	0.047
851211		-2.936	0.224	-0.021	-0.049	0.041
851212		-2.934	0.226	-0.021	-0.048	0.042
861202		-2.877	0.199	-0.015	-0.044	0.059
861203		-2.864	0.205	-0.023	-0.048	0.062
861204		-2.857	0.206	-0.029	-0.034	0.045
861206		-2.866	0.208	-0.031	-0.032	0.056
861207		-2.867	0.202	-0.026	-0.039	0.056
880112		-2.770	0.150	-0.026	-0.055	—
880113		-2.768	0.145	-0.023	-0.045	0.058
880114		-2.754	0.148	-0.037	-0.044	0.065
880115		-2.765	0.146	-0.019	-0.037	—
880121		-2.741	0.146	-0.042	-0.043	0.056
881207		-2.844	0.194	-0.036	-0.047	0.073:
881208		-2.842	0.195	-0.032	-0.056	0.054:
891221		-2.898	0.201	-0.007	-0.078	0.094
891223		-2.906	0.218	-0.041	-0.032	—
891224		-2.905	0.215	-0.029	-0.026	0.066
891226		-2.910	0.217	—	—	—
891227		-2.904	0.213	-0.008	-0.032:	0.063
891228		-2.901	0.214	-0.011	-0.056:	0.064
801210	16.5	-2.702	0.179	-0.052	-0.049	0.044
801211		-2.703	0.180:	-0.048	-0.054	0.052
801212		-2.704	0.177	-0.047	-0.054	0.051:
801213		-2.705	0.181	-0.054	-0.054	0.039
821207		-2.836	0.232	-0.023	-0.044	0.061
891224		-2.842	0.242	0.015:	-0.072:	—
821207	21.5	-2.802	0.249	-0.003	-0.067	0.067
891224		-2.822	0.248:	0.024	-0.044:	—
891221	28.1	-2.783	0.253	0.019	-0.029:	—

$^{10}\log(\text{intensity})$. There is no evidence at all of variability on timescales of one or two weeks or less: the RMS variations within an observing run are typically of the order of $\sim 1\%$ in $V-B$, $B-L$ and $L-U$, $1-2\%$ in V and $\sim 3\%$ in $U-W$. Any real variations on timescales of one week must therefore be less than about 0.01 to 0.02 mag, and we may safely average the values obtained in one observing run. If Fairall 9 was observed just once or twice in a particular run the error is taken to be that of an individual measurement (see Paper I). The average values of V , B , L , U and W were corrected for interstellar reddening applying the formulas given by Lub & Pel (1977) and Lub (1977) and are listed (in mJy) in Table 2. In order to avoid confusion, magnitudes in the traditional Johnson UBV system are distinguished by a subscript J.

2.2. Spectroscopy

The photometric measurements were always accompanied by spectroscopic observations. The latter were usually done in the

middle of the photometric run, such that the photometry and spectroscopy can be considered as quasi-simultaneous. The observations were carried out with the ESO 3.6 m telescope (1980 and 1981), and the 1.5 m spectroscopic telescope (from 1982 onward). Until and including 1986 an IDS detector and B&C spectrograph were used, but from 1988 the IDS was substituted by a high-resolution CCD. Normally, the observations were done with a $110 \text{ \AA/mm}$ grating, resulting in a spectral resolution of about $8 \text{ \AA}$ for the IDS + B&C combination, and about $3 \text{ \AA}$ for the more recent CCD data. (The only exception occurred in August 1980, when a $178 \text{ \AA/mm}$ grating was used.) If possible we made, in the same observing run, at least one exposure in the blue, approximately covering the wavelength range $3700-5800 \text{ \AA}$ and one in the red ($5000-7000 \text{ \AA}$), such that all Balmer lines were included. However, in some observing runs no red spectra could be taken due to unfavourable weather conditions. The observing log is given in Table 3. The flux scale was determined by observing one or more standard stars each night; a He-Ar arc spectrum was taken immediately before or after observing Fairall

Table 2. I.S.R. corrected continuum flux densities (in mJy)

Mean date	<i>V</i> 5441 Å	<i>B</i> 4298 Å	<i>L</i> 3837 Å	<i>U</i> 3623 Å	<i>W</i> 3235 Å
79.97	18.63 ± 0.28	15.97 ± 0.18	18.33 ± 0.31	19.66 ± 0.31	19.47 ± 0.45
80.61	17.72 ± 0.23	14.98 ± 0.17	17.60 ± 0.26	18.85 ± 0.26	18.29 ± 0.26
80.95	14.93 ± 0.34	11.73 ± 0.35	13.47 ± 0.47	14.44 ± 0.58	13.79 ± 0.65
81.93	14.59 ± 0.20	11.79 ± 0.22	13.35 ± 0.28	14.30 ± 0.27	13.76 ± 0.34
82.96	10.54 ± 0.10	7.46 ± 0.07	7.91 ± 0.06	8.63 ± 0.09	8.32 ± 0.04
83.94	8.05 ± 0.25	5.00 ± 0.12	4.67 ± 0.01	5.07 ± 0.16	5.05 ± 0.05
84.98	7.68 ± 0.06	4.67 ± 0.06	4.10 ± 0.12	4.30 ± 0.12	4.18 ± 0.01
85.95	9.39 ± 0.03	6.55 ± 0.06	6.77 ± 0.04	7.19 ± 0.03	6.91 ± 0.07
86.93	10.99 ± 0.15	8.00 ± 0.08	8.44 ± 0.15	8.76 ± 0.13	8.19 ± 0.17
88.04	14.05 ± 0.32	11.67 ± 0.28	12.44 ± 0.50	13.08 ± 0.51	12.38 ± 0.51
88.94	11.59 ± 0.04	8.63 ± 0.01	9.29 ± 0.04	9.92 ± 0.08	—
89.98	10.07 ± 0.08	7.19 ± 0.13	7.51 ± 0.14	8.05 ± 0.39	7.17 ± 0.21

Table 3. Observing log (spectroscopy)

Date	Telescope (m)	Spectral range (Å)	Dispersion (Å/mm)
25 Aug. 80	3.6	3800–7300	178
11 Dec. 80	3.6	3700–5800	114
12 Dec. 80	3.6	4900–7000	114
23 Dec. 81	3.6	3900–6000	114
24 Dec. 81	3.6	5000–7100	114
17 Dec. 82	1.5	3700–5900	114
07 Dec. 83	1.5	3700–5900	114
09 Dec. 83	1.5	4800–7000	114
24 Dec. 84	1.5	3800–6000	114
27 Dec. 84	1.5	4900–7100	114
13 Dec. 85	1.5	3700–5900	114
15 Dec. 85	1.5	4800–7000	114
16 Dec. 85	1.5	4800–7000	114
25 Nov. 86	1.5	3800–6000	114

9, in order to provide an accurate wavelength calibration. The data reduction was done using the IHAP software package, installed on the H.P. computers at ESO headquarters, Munich.

The flux calibration of spectroscopic observations is notoriously troublesome, which is immediately clear when comparing the spectra taken at different epochs: the fluxes of presumably constant lines like [O III] $\lambda 5007$ differ by as much as a factor of 2, even if the spectra were formally flux-calibrated with the help of standard stars. Although one could proceed by giving up the absolute flux calibration and just normalize all line fluxes to [O III] $\lambda\lambda 4959$ and 5007, this has some disadvantages (see, for example, Baribaud & Alloin 1990). In our specific case there is another possibility. Since we have photometric data taken only one or two days apart from the spectra, we could try to calibrate the flux scale of the spectra utilizing the Walraven data. The choice of the right Walraven band is crucial: since the *VBLUW* measurements are normally done using an aperture of 11'', and the spectra with an aperture of 4'', complications arise for those

bands in which an appreciable contribution of galaxy-light is expected. This is true for *V* and, although less seriously, for *B*. Moreover, the *V* band is also contaminated by strong emission lines. On the other hand *U* and *W* fall outside the wavelength range of the spectra (which start at ~ 3700 to 3800 Å); thus we are left with the *L* band. Indeed, this is the natural choice, because the galaxy contribution is negligible (see Sect. 3) and no important emission lines fall inside the *L* band. We therefore corrected the fluxes of the spectra, by making the continuum level at 3837 Å equal to the photometrically observed *L* level. This method turns out to be quite successful, because now the [O III] $\lambda 5007$ fluxes have a spread of only 5%: we find a flux, averaged over all spectra, of $(2.33 \pm 0.12) 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. All line fluxes were thus corrected, and the resulting values are given in Table 4. In Table 5 the luminosities of selected lines, determined from the corrected fluxes, are listed.

The average [O III] $\lambda 5007$ flux differs by not more than 6% from the value of $2.18 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ quoted by Stirpe (1989), which reinforces our confidence in the calibration procedure we have followed. Other values found in the literature give on average a similar line flux, although with a scatter of $\pm 30\%$: Kollatschny & Fricke (1985) give $F(\lambda 5007) = 2 10^{-13}$, Wamsteker et al. (1985) $1.6\text{--}2.1 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. Earlier determinations of the luminosity (used by Rudy 1984) can be found in Hawley & Phillips (1978) – $L(\lambda 5007) = 6 10^{41}$ – and Ward et al. (1978) – $L(\lambda 5007) = 6.9 10^{41} \text{ erg s}^{-1}$ (both values converted to a Hubble parameter of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, which is used in this paper). This should be compared with the average of our data, $L(\lambda 5007) = (5.4 \pm 0.3) 10^{41} \text{ erg s}^{-1}$.

Using the well-defined narrow lines in all the available spectra we have calculated the mean observed redshift; we find $z = 0.04588 \pm 0.00005$, or $cz = 13764 \pm 15 \text{ km s}^{-1}$, where the uncertainty is the standard deviation of the mean. Corrected to the galactic centre this becomes: $z = 0.04535 \pm 0.00005$ ($13605 \pm 15 \text{ km s}^{-1}$). This agrees very well with the values given by Griensmith & Visvanathan (1979): 13735 ± 120 and $13590 \pm 120 \text{ km s}^{-1}$, respectively.

The narrow emission lines in Fairall 9 have a width of $\sim 500 \text{ km s}^{-1}$ (van Groningen 1984), i.e. close to the resolution of most of our spectra. Because of this relatively low resolution we did not attempt to investigate in detail the line profiles.

Table 4. Line fluxes

Date	λ_{rest}	Identification	FWHM	Flux	– EW
yymmdd	(Å)		(Å)	10^{-16} $\text{erg s}^{-1} \text{cm}^{-2}$	(Å)
801211	3654.5	[S II]	13.4	—	—
861125	3727	[O II]	19.6	548	7.29
811223	3771	H11	—	—	—
801211	3869.7	[Ne III]	—	—	—
811223			9.9	—	—
831207			7.7	—	—
841224			12.3	592	10.8
851213			11.1	—	—
861125			11.7	711	6.48
801211	3888.8	He I, H8	—	—	—
811223			11.4	—	—
801211	3969	[Ne III], He	60.5	1440	9.65
811223			11.1	350	2.08
831207			—	—	—
851213			6.5	—	—
801211	4101.7	H δ , [S III] λ 4077	66.9	2660	20.1
811223			—	1820	13.2
821217			27.9	1870	19.5
851213			—	—	—
861125			5.2	1240	13.0
801211	4340.5	H γ , [O III] λ 4363.2	—	5380	43.4
811223			—	3730	28.7
821217			—	2940	29.2
831207			—	2190	29.8
841224			36.4	837	17.9
851213			—	2490	43.5
861125			43.8	3030	33.6
801211	4570	Fe II, He II λ 4685.7	—	4850	41.1
811223			—	4470	40.3
821217			—	5610	68.4
831207			—	2720	39.5
841224			—	2460	58.3
851213			—	2540	45.6
800825	4861.3	H β	64.2	11900	51.8
801211			63.1	8790	69.2
811223			58.7	7710	61.2
821217			46.8	7580	77.3
831207			47.8	3770	50.0
841224			101.0	1560	31.1
851213			63.4	3660	57.3
861125			56.6	3696	—
880116			—	6688	—
800825	4958.9	[O III]	14.3	583	2.80
801211			10.0	626	5.00
811223			9.3	570	4.81
821217			10.0	609	6.23
831207			11.3	639	7.89
841224			11.1	616	10.00
851213			10.5	695	10.90
861125			12.7	750	—
800825	5006.8	[O III]	13.4	2420	11.1
801211			11.8	2260	19.3
811223			11.5	2390	20.3
821217			11.5	2420	25.1
831207			11.3	2450	29.2

Table 4 (continued)

Date yymmdd	λ_{rest} (Å)	Identification	FWHM (Å)	Flux 10^{-16} $\text{erg s}^{-1} \text{cm}^{-2}$	—EW (Å)
841224			11.7	2140	37.0
851213			11.7	2190	35.3
861125			11.6	2360	—
801211	5180	Fe II	—	3560	40.5
811223			—	2700	32.8
831207			—	3760	75.7
841224			—	2360	61.1
851213			—	2240	48.7
811224	5720.9	[Fe VII]	11.2	217	2.91
831209			13.1	271	5.39
841227			11.6	198	5.19
851216			17.8	147	3.26
801212	5875.6	He I	—	3910	44.7
811224			89.0	2010	26.6
831209			—	1280	26.0
851216			—	1310	28.8
801212	6085.3	[Fe VII], [Ca v]	22.1	—	—
811224			14.1	342	4.66
831209			11.3	366	7.41
841227			16.2	240	6.18
851216			10.5	266	5.77
800825	6562.8	H α , [N II]	—	72800	404
801212			81.7	45600	432
811224			78.1	35200	445
831209			67.6	26700	466
841227			85.3	13800	316
851216			83.5	17800	323

Table 5. Line luminosities (in $10^{42} \text{ erg s}^{-1}$)

Line	λ_0 (Å)	Date (yymm)							
		80.08	80.12	81.12	82.12	83.12	84.12	85.12	86.11
[Ne III]	3870	—	—	—	—	—	0.14	—	0.16
[Ne III]	3969	—	0.33	0.08	—	—	—	—	—
H δ	4102	—	0.61	0.42	0.43	—	—	—	0.28
H γ	4340	—	1.23	0.85	0.67	0.50	0.19	0.57	0.70
Fe II	4570	—	1.11	1.02	1.28	0.62	0.56	0.58	—
H β	4861	2.72	2.01	1.77	1.74	0.86	0.36	0.84	0.85
[O III]	4959	0.13	0.14	0.13	0.14	0.15	0.14	0.16	0.18
[O III]	5007	0.56	0.52	0.55	0.56	0.56	0.49	0.50	0.54
Fe II	5180	—	0.82	0.62	—	0.86	0.54	0.51	—
[Fe VII]	5721	—	—	0.05	—	0.06	0.05	0.03	—
He I	5876	—	0.90	0.46	—	0.29	—	0.30	—
[Fe VII]	6085	—	—	0.08	—	0.08	0.05	0.06	—
H α	6563	16.68	10.44	8.07	—	6.12	3.15	4.07	—

3. Results and conclusions

3.1. Variability of the continuum

In Fig. 1 we show the light curves of V and the colour-indices $V-B$, $B-L$, $L-U$ and $U-W$. For easy reference the visual Johnson magnitude is also shown. It was calculated using the

equation $V_J = 6.886 - 2.5V - 0.082(V-B)$, which was derived from a least-squares fit using the standard stars of the Walraven system (Lub & Pel, unpublished).

According to Glass (1986), Fairall 9 had a visual magnitude $V_J = 13.5$, corresponding to $V = -2.65$, in the period around October 1979 and had dimmed to 14.3 ($V = -2.97$) in October

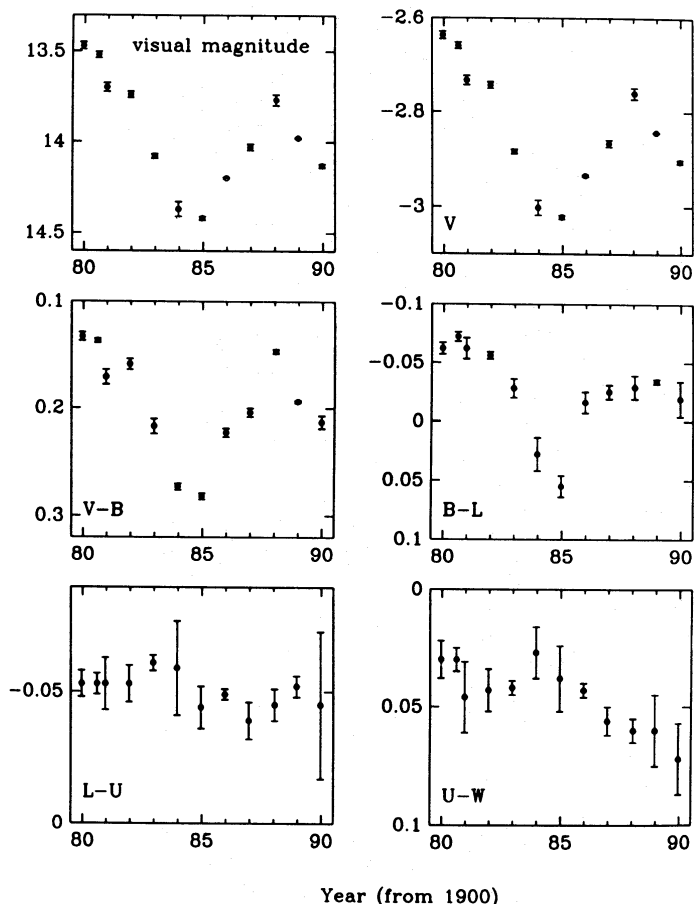


Fig. 1. Walraven light curves of Fairall 9 over the period 1979–1989. In the upper left panel the light curve is given in magnitude units (calculated from Walraven V and $V-B$). The ordinate of the other panels is given in units $\log$ (intensity)

1983. These data are in excellent agreement with the light curves of Fig. 1. There also exists some photometry done in the period 1977–1979: Martin et al. (1978), using a $14''.2$ aperture, determined a visual magnitude $V_j = 13.2$ ($V = -2.53$) in February 1977. Apparently Fairall 9 remained very bright in the period 1977–1979, because in August 1979 Griensmith & Visvanathan (1979) found $V_j = 13.15$, or $V = -2.51$ (in a $9''.6$ aperture). These early data appear to concur on the fact that Fairall 9 was significantly brighter in the period 1977–1980 than it has been ever since (up to 1990).

The regularity of the light curves is striking; it is also evident from Fig. 1 that the $V-B$ colour varies in phase with V . However, this does not necessarily imply that the nuclear radiation changes colour. The spectral shape of the variable component, obtained by subtracting the December 1984 values (when Fairall 9 was at its weakest) from $VBLUW$ of each period, is almost constant, with $V-B \sim 0$ (see Fig. 2). There is a marginal indication that the variable component changed colour in the periods close to the minimum reached in 1984, but the relative errors of the fluxes after subtraction of the 1984 values and, thus, of the colour indices are very large (as can be easily deduced from Table 2).

The colour changes in $V-B$ and $B-L$ are most likely due to the varying ratio of nuclear to stellar radiation in V and B , or more generally of the variable component(s) to the constant

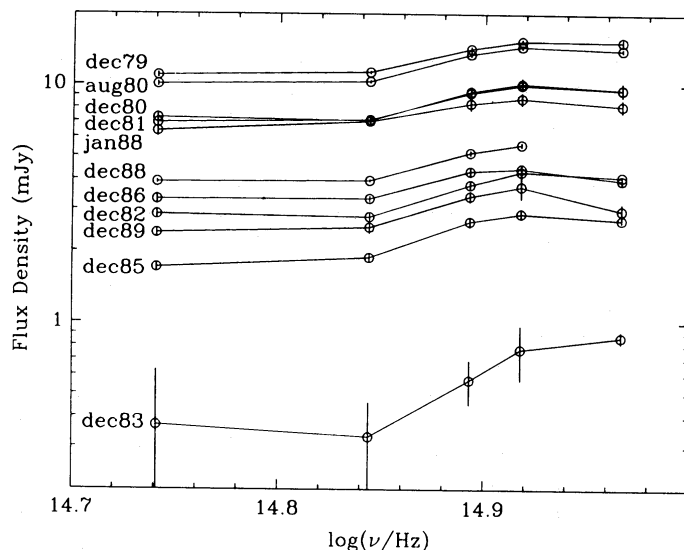


Fig. 2. The spectral shape of the variable component in mJy (the 1984 $VBLUW$ values are subtracted). The error bars, calculated from Table 2, are generally smaller than the plotted datapoints, except for the 1983 values

component(s). The stellar component is entirely negligible below $\sim 4000 \text{ \AA}$, compared to the radiation coming from the nucleus. This can be deduced from the $VBLUW$ measurements that were made at different apertures (see Table 1). At larger apertures the $V-B$ and $B-L$ colours are redder, due to the growing influence of the stellar component. Assuming an exponential light distribution $I_{\text{gal}}(r) = I_0 \exp(-r/\theta)$, we can reproduce the colours of the galaxy outside the nucleus (by subtracting the smallest aperture from the larger ones), if we take $\theta = 5''.25$. The galaxy contribution in the $11''.6$ aperture (in mJy, and corrected for interstellar reddening) is then: $F_V = 2.06$, $F_B = 1.19$, $F_L = 0.67$, $F_U = 0.38$, and $F_W = 0.1$. This corresponds $V_j = 15.6$ within a radius of $5''.8$ (i.e. an absolute visual magnitude of -20.1) and $(B-V)_j = 0.67$, which is very similar to the value $(B-V)_j = 0.72$ given by Griensmith & Visvanathan (1979). Note that U_{gal} and especially W_{gal} are quite uncertain, but it is clear that the galaxy contributes little in the L , U and W bands anyway. Since starlight and some strong emission lines ($\text{H}\beta$, $[\text{O III}]$) contribute significantly to V , whereas L , U and W contain significant contributions from potentially troublesome components like high-order Balmer lines, the Balmer continuum and Fe II features, in the following the optical continuum is always represented by B .

Summarizing, there is strong evidence that the nuclear $V-B$ remained constant over the whole ten year period, even though the strength of the continuum changed drastically. A similar effect, but in the ultraviolet, was noticed by Clavel et al. (1989): the spectral index between 1338 and $1826 \text{ \AA}$ was constant in the period 1978–1987, whereas the ratio of maximum to minimum intensity was as high as ~ 33 . Both these facts appear to point at a nuclear variability that conserves spectral shape, at least over the range 1000 to $6000 \text{ \AA}$. However, there is the problem that the amplitude of the variations is much larger in the UV than in the optical (~ 20 against 3.8 for our data, if in both cases we use the maximum and minimum intensity of periods in which both UV and Walraven observations were made, i.e. around July–August 1980 and the end of 1984). This kind of hardening of the UV-to-optical continuum when the object is brighter is also seen in

NGC 5548 (Peterson et al. 1991). It is not sufficient to remove the contribution of starlight (as determined above): the ratio of maximum and minimum nuclear flux is then of the order of at most 5. Moreover, correction for starlight alone does not give a constant nuclear $V-B$. Clavel et al. (1989), who already noticed this problem, suggested that perhaps the galaxy contribution to the optical intensity is higher than expected. Our new data do not support this possibility, which gives more credit to their second hypothesis – that the excess flux is due to the IR power law discussed by Edelson & Malkan (1986). We stress that the data presented here confirm the difficulties discussed by Clavel et al. (1989) for the geometrically thin accretion disk model.

It appears, then, that the nuclear continuum varies strongly, but with an amplitude that does not depend on wavelength, that is without changing the spectral index. A further check on this can be obtained by cross-correlating B with the ultraviolet continuum at 1338 Å given by Clavel et al. (1989). It should be remarked that the cross correlation analysis carried out here and in the following only makes sense if the light curves of Fairall 9 are very regular; fortunately there is abundant evidence (cf. also the UV light curves of Clavel et al. 1989) that this is indeed the case. The correlation function (CCF) is shown in Fig. 3, in which also the cross correlations of B with V and W are given for comparison. For F_{uv} as well as V and W the time lags are 18 ± 100 d (also L and U , not shown in Fig. 3, have $\sim$ zero time lags). The errors in the lag, determined following the recipe of Gaskell & Peterson (1987), are rather large, but this is not surprising considering the limited amount of Walraven data (in practice one point per year; this is also true for the emission line data discussed in the next section). We conclude that, considering the time resolution of our data, the variations in the optical and UV continuum are indeed simultaneous. Again this is hard to explain in the framework of the thin disk model, where delays between the UV radiation, originating mainly in the hot inner zone and the optical emission, predominantly produced in the outer regions, are expected.

Although the simultaneity of all Walraven bands indicates that the bulk of the optical radiation varies in phase, the colour indices may still reveal the presence of secondary components that change on different time scales. Walraven L falls just redward

of the Balmer discontinuity at 3646 Å for a zero-redshift object. The redshift of Fairall 9 is small enough for this to remain valid. U and W fall in the wavelength range of the “3000 Å” or “small” bump, which is a characteristic feature in the spectra of Seyfert galaxies and quasars (Netzer 1990). This bump, clearly seen in Fairall 9 (Fig. 2) is a composite of the Balmer continuum ($\lambda < 3646$ Å) and Fe II blends (the Fe II complex redward of Mg II $\lambda 2798$). Differential changes of the three colours $B-L$, $L-U$ and $U-W$ may therefore contain information on the different behaviour of the various components.

In Fig. 4 we present the CCFs of B with the Walraven colours. The delay of $V-B$ is 0 ± 90 d, and this result reinforces our earlier conclusion that V and B vary perfectly in phase. There is marginal evidence for a time lag of $B-L$ with respect to B , although the result of the CC analysis, 75 ± 100 d, is consistent with a zero time lag. Since $B-L$ traces the changes of the high-order Balmer lines we discuss this result further in Sect. 3.2 and 3.3.

The ultraviolet colour index $L-U$ has remained almost constant over the whole ten-year period, although there is a very small amplitude (~ 0.03 mag) variation, which is shifted by more than two years with respect to the flux variations. There is also some evidence that the non-stellar component has become gradually redder in the $U-W$ index (Fig. 1). Cross correlation with B gives 910 ± 110 d for the $U-L$ and > 1000 days for the $U-W$ delays (see Fig. 4). The result for $L-U$ is very uncertain due to the very small amplitude of the variations, but $U-W$ appears to be changing really with a very large time delay.

3.2. Emission line variability and time lags

In Fig. 5 we show the light curves of B , of $H\beta$ and $H\alpha$, and, for comparison, of $[O III] \lambda 5007$. The accuracy of the line flux calibration is seen from the constancy of the $[O III]$ flux. As a general rule the strength of the broad permitted lines correlates with the strength of the continuum, whereas the narrow forbidden lines stay constant. This is of course a well-known fact (de Bruyn 1980; French & Miller 1980; Peterson et al. 1985; Stirpe et al. 1988); however, due to the regular and slow variation of Fairall 9

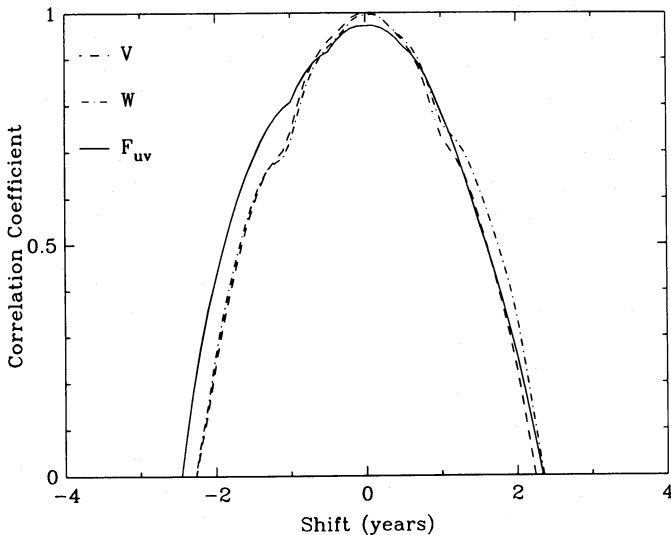


Fig. 3. The cross correlation function of Walraven B with V , W and F_{uv} (1338 Å). The UV data are taken from Clavel et al. (1989)

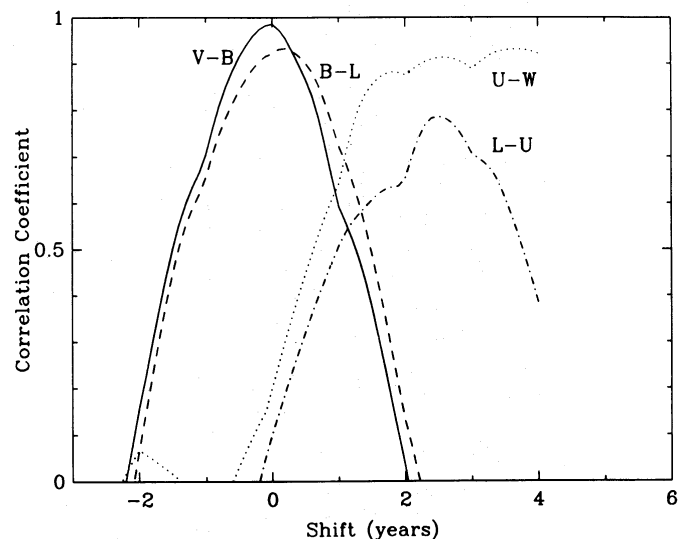


Fig. 4. The CCF of B with the Walraven colour indices

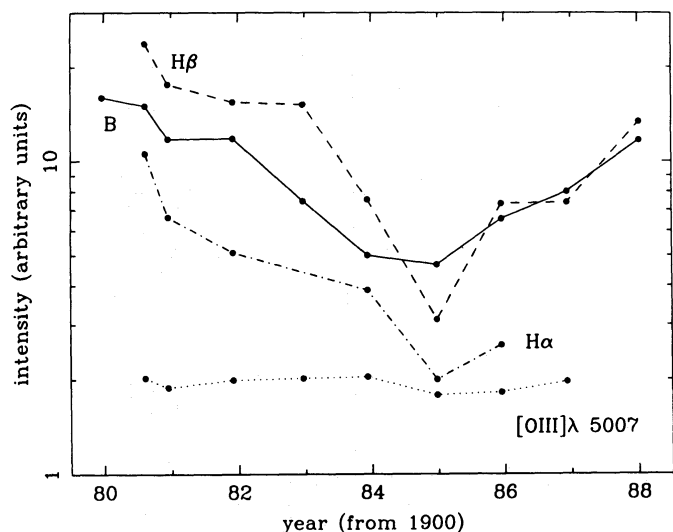


Fig. 5. Light curves of the continuum (B), $H\alpha$ and $H\beta$, and $[O III] \lambda 5007$. The ordinate is in arbitrary units

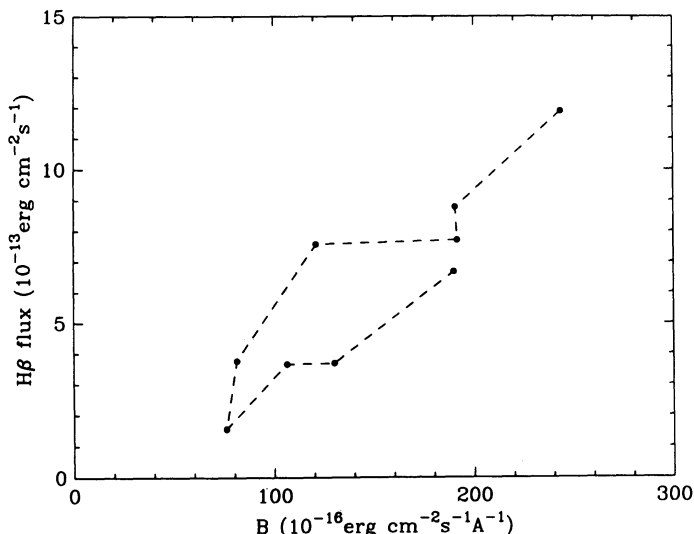


Fig. 6. Correlation of the changes in the continuum and $H\beta$. The dashed line connects successive observing periods

(the period of the variation being of the order of 8 yr) it is possible to compare the light curves in more detail. Although the data points are rather widely sparsely in time (see Fig. 5), a time delay between the changes of the continuum – represented by B – and the Balmer lines is, with some difficulty, discernible. The delay between B and $H\beta$ is best visible, and visual inspection of Fig. 5 suggests that $H\beta$ lags behind the continuum by at least six months and possibly more. A very convenient way of detecting delays is to plot the $H\beta$ flux directly against the continuum flux density (Fig. 6). We note that the curve in Fig. 6 describes a loop just as expected if the continuum and broad emission lines are out of phase: this is of course nothing but a Lissajous figure, considering the sine-like light curve and a sampling that is much finer than the “period”. Another example of this kind of loop is given by Clavel et al. (1990) (their Fig. 5).

The CC between B and $H\beta$ (shown in Fig. 7) gives a time lag of 270 ± 150 d. As a further check we also correlated $H\beta$ with the $1338 \text{ \AA}$ UV flux of Clavel et al. (1989); this CCF is also shown in Fig. 7. Since the UV and optical continua vary simultaneously (see Sect. 3.1) a similar time lag is expected; in fact we find 220 ± 124 d, which agrees well within the errors with the previous estimate of 270 ± 150 d.

A delay time of this magnitude is somewhat larger than the independent estimates of 155 ± 45 d by Clavel et al. (1989), and 167 ± 61 d by Koratkar & Gaskell (1989), but considering the large uncertainty (and the different time intervals used), it is fair to say that all estimates concur on a delay in the range of six to nine months. Photoionization model calculations by Clavel & Santos-Lleó (1990) yield 100 light-days for the mean distance of the BLR gas to the ionizing source, which agrees well with the observed lag of the ultraviolet lines but may be too small for the optical lines.

The CCFs of B with $H\alpha$ and $H\gamma$ are given in Fig. 8a. Unfortunately, the CCF of $H\alpha$ is very broad (due to the incompleteness of the $H\alpha$ light curve), but there is some indication that the $H\alpha$ time lag is larger than that of $H\beta$ (~ 400 against ~ 270 d). On the contrary, the correlation of B with $H\gamma$ peaks at 100 ± 120 d.

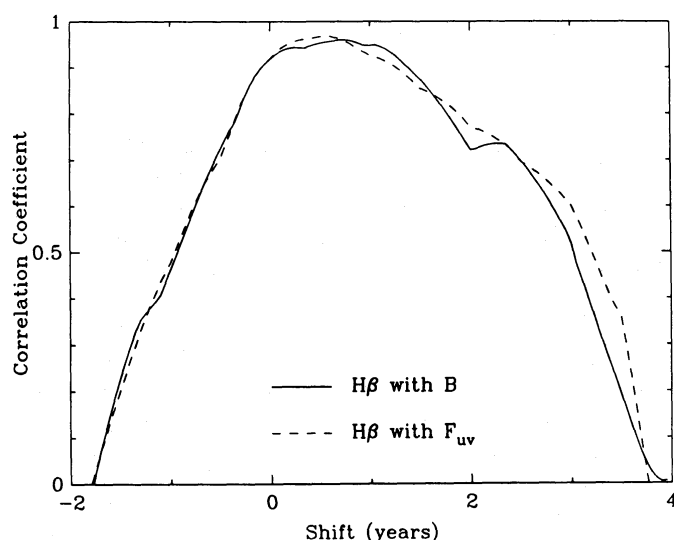


Fig. 7. The CCF of the optical and UV continuum (B and F_{uv}) with $H\beta$

As a result of this the Balmer decrement, the ratio of the $H\alpha$ and $H\beta$ fluxes, is variable with time as well. This is not at all unexpected (it was discussed by Antonucci & Cohen 1983 and Stripe 1989), as regions with different physical conditions (density, temperature) dominate the flux at various stages of the nuclear activity; the Balmer decrement strongly depends on collisional and optical depth effects and, therefore, on temperature and electron density (see e.g. Drake & Ulrich 1980; Kwan & Krolik 1981; Zheng & Puetter 1990). The ratio $H\alpha/H\beta$ was highest around 1984, when Fairall 9 reached its minimum ($H\alpha/H\beta \sim 7-8$), and lower when the object was brighter ($H\alpha/H\beta \sim 5-6$). Such a behaviour was also noticed by Antonucci & Cohen (1983) and may be consistent with the early data, when Fairall 9 was definitely brighter and the ratio closer to 2.5–3 (Hawley & Phillips 1978; Ward et al. 1978). Although the limited quality of our spectroscopic data does not permit a detailed analysis of the

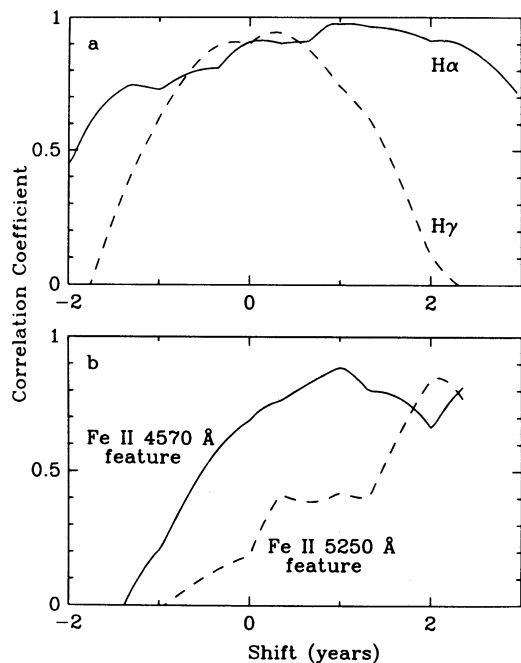


Fig. 8. **a** The CCF of B with $H\alpha$ and $H\gamma$ and **b** with the Fe II line complexes at 4570 and 5250 Å

Balmer decrement, it appears that the high $H\alpha/H\beta$ ratio is mostly due to a very broad component, which varies much more drastically (and on a different time scale) in the higher Balmer lines. Strongly variable broad components were also found in e.g. C II $\lambda 1549$ in NGC 4151 (Clavel et al. 1990): the changes in the wings of C IV occur earlier than in the core and, moreover, are stronger. The importance of a broad component that caused a low $H\delta/H\beta$ ratio was noticed by van Groningen (1984). The effect is particularly clear in the observations of 1983 and 1984: the shapes of $H\alpha$ and $H\beta$ were entirely different (in fact, in 1984, the broad $H\beta$ component all but disappeared, while it was still relatively strong in $H\alpha$), whereas $H\alpha$ and $H\beta$ had very similar shapes in the bright phase around 1980 to 1981. It is worth noting here that there appears to be a strong relation between the magnitude of the time lag and the Balmer sequence, going from $H\alpha$ via $H\beta$ and $H\gamma$ to the high-order Balmer lines (the $B-L$ colour).

Averaged over all periods we find that the ratio $H\alpha:H\beta:H\gamma:H\delta$ are 6.1:1:0.52:0.26. Although the Balmer ratios do not give a unique determination of the physical conditions in the BLR (the results of calculations are highly model-dependent), we nevertheless remark that the observed ratios are consistent with an average density of $10^{10.5} \text{ cm}^{-3}$ (in Drake & Ulrich's 1980 model with $T=10^4 \text{ K}$, $\tau_{L\alpha}=10^5$). Photoionization calculations by Clavel & Santos-Lleó (1990) reproduce well the UV-optical spectrum of Fairall 9 with a composite model of the BLR that includes both a low- ($10^{9.5} \text{ cm}^{-3}$) and a high-density (10^{11} cm^{-3}) region. It is interesting that the density of the latter region – which in their model accounts for the bulk of the Mg II $\lambda 2798$ and Balmer line flux – agrees well with the above independent estimate based on the Balmer decrement.

Other broad emission lines, e.g. He I $\lambda 5876$, are available as well, but their behaviour is less clear due to their relative weakness. In many cases (in particular, when Fairall 9 was in the low state of activity) it was not possible to derive fluxes for such

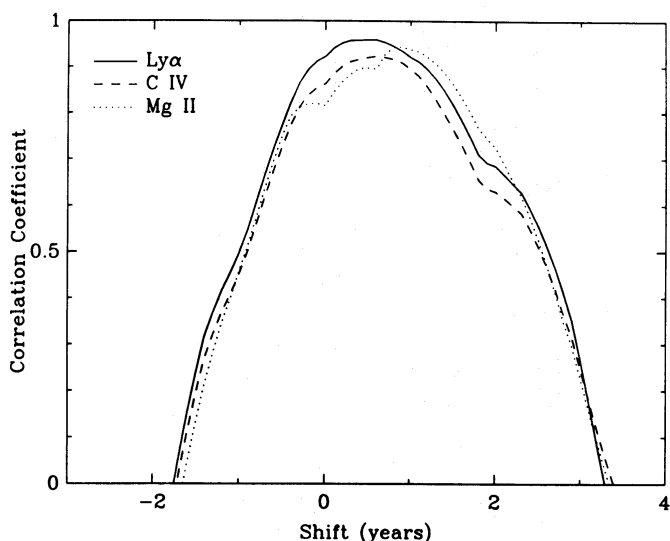


Fig. 9. The CCF of B with $Ly\alpha$, C IV and Mg II

lines. It is also clear that the Fe II complexes around 4600 and 5200 Å are variable (cf. Alloin et al. 1988 for the case of Akn 120), but perhaps with a significantly larger time delay with respect to the continuum than the Balmer lines. Cross correlation of Fe II $\lambda 4570$ and Fe II $\lambda 5190 + 5320$ (see Fig. 8b) gives 365 and 750 days, respectively. Admittedly the errors are unknown (but large), due to the fact that we were not always able to measure these features accurately (they are very broad but shallow); it is worth pointing out, however, that these time lags agree with the large delays found for $U-W$ (presumably due to Fe II lines in the W band, see Sect. 3.1). For this reason we attach some significance to this result: it may well be that the different delays may contain information about the structure of the broad line region.

3.3. Conclusions

We have seen that quite significant time delays are present in the light curves of the broad permitted lines, as compared to the continuum, be it in the UV or in the optical. Moreover, there is strong evidence that these delays are not all the same. In order to get as much information as possible we also did a cross correlation between B and $Ly\alpha$, C IV $\lambda 1549$ and Mg II $\lambda 2798$, using the line data of Clavel et al. 1989. The results are shown in Fig. 9. Both $Ly\alpha$ and C IV have a time lag of $220 \pm 140 \text{ d}$ with respect to B , while the delay of Mg II appears to be somewhat larger ($330 \pm 140 \text{ d}$).

It has been noticed that in NGC 4151 (Clavel et al. 1990) and NGC 5548 (Clavel et al. 1991) the delay times correlate with the type of line. In NGC 5548, for instance, the high-ionization lines (N V $\lambda 1240$ and He II $\lambda 1640$) show the strongest variations and the shortest delays (4–10 d), while the low-ionization line Mg II varies with a much smaller amplitude and with a much larger delay (34–72 d). Intermediate-ionization lines ($Ly\alpha$, C IV $\lambda 1549$ and C III $\lambda 1909$) have intermediate variation amplitudes and delays. The data discussed here suggest that something similar is happening to Fairall 9, although the timescales involved are much larger (by a factor of at least 10). In order to see this more clearly we have brought all the time lags determined in the present work together in Fig. 10.

Although the large uncertainties prevent us from attaching much significance to the magnitudes of the time lags, we can be more confident of the differences between the various delays found. In fact, we have used different and independent data (Walraven photometry, spectroscopy), and also data collected by others (Clavel et al. 1989), but without exception the various cross correlations produce consistent results. A quite coherent picture then arises from Fig. 10.

(i) The entire continuum varies in phase, from the optical to the ultraviolet, and possibly maintains its shape as well. This is suggested by the constancy of both the UV and the optical spectral index. The varying ratio of UV to optical flux must then be explained by the presence of a constant component that is important only in the optical. Since the galactic starlight from Fairall 9 is not sufficiently strong the most likely candidate is the IR power law of Edelson & Malkan (1986).

(ii) The Fe II features reflect the continuum changes, but at much later times ($> 1-2$ yr, say). It is perhaps no coincidence that Clavel et al. (1989) found high time lags (~ 400 d) for the infrared K and L fluxes, which would point at a common physical location of the Fe II gas and the IR emission region.

(iii) Other lines ($H\beta$, Ly α , C IV) have time lags that are much smaller, but still considerable ($\sim 6-9$ months). The Mg II line may be slightly more delayed, although only marginally so.

(iv) There appears to be a quite strong correlation between the time delays and the Balmer lines, $H\alpha$ changing later than $H\beta$, which in turn lags behind $H\gamma$. Finally, the higher-order Balmer lines (represented by $B-L$) respond to continuum changes most rapidly (time lag of ~ 2 months). As discussed in Sect. 3.2 this result may be related to the changes in the Balmer decrements found by other authors. Its cause is possibly a very broad component produced close to the nucleus. The different delays may then be understood if the Balmer lines contain several components with different Balmer decrements.

What makes Fairall 9 stand apart from other Seyfert galaxies are the large time lags between the continuum and the broad permitted lines compared to delays of the order of 30 days or less in objects like NGC 4151 and NGC 5548 (Ulrich et al. 1984; Clavel et al. 1990, 1991) and a long "pseudo"-period of about eight years combined with a very regular variation of the

continuum strength. It is probably no coincidence that Fairall 9 is also among the most luminous Seyfert galaxies, and in many ways resembles a quasar. It will be of interest to continue monitoring Fairall 9 in order to establish that the regularity of the light curves is indeed a characteristic of this object. If so, it will be relatively easy to get a wealth of information on the different delay timescales.

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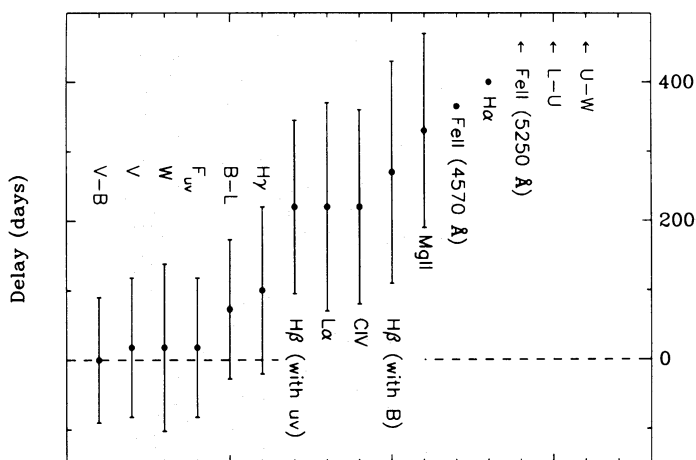


Fig. 10. Time delays determined from the cross correlations described in the text

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