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Astron. Astrophys. 211, 310–314 (1989)

ASTRONOMY AND ASTROPHYSICS

Emission line variation in the Seyfert galaxy Fairall 9 and the presence of broad [O III] emission *

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Received August 2, accepted September 23, 1988

Summary. We present two high quality spectra of the Hβ region in the Seyfert 1 galaxy Fairall 9, separated by a period of 4 years. The variation of the broad lines is discussed, and in particular that of the Fe II lines of multiplet 42. The difference spectrum shows clearly Fe II (42) λ5018 and λ5169 with equal intensity. There is a strong, broad (4000 km s^{-1}) wing present under the [O III] λ5007 line, which varied only by a small amount. We show that this variation is entirely due to the variation of Fe II λ5018 and that the remainder of the [O III]-wing has not varied. On this basis we argue that the wing is not caused by the Fe II (42) λ5018 line, nor by any other Fe II lines, but that we observe high velocity [O III]-emitting material. From the lack of variation in this component a minimum distance to the source can be set of 1.3 pc. Other features of the difference spectrum are also discussed.

Key words: galaxies: active – galaxies: Seyfert – lines: profile – spectrophotometry

1. Introduction

Fairall 9 is an intrinsically very bright Seyfert 1 galaxy (Fairall, 1977; West et al., 1978), with redshift $z = 0.0461$ (van Groningen, 1984). Its flux has decreased for many years until 1984 (de Ruiter and Lub, 1986; Kollatschny and Fricke, 1985; Wamsteker et al., 1985; Glass, 1986; Clavel et al., 1988). As well as the continuum, the broad lines have also weakened in intensity, as is to be expected from a photoionization model. Correlated variations in the continuum and strongest lines have been observed in many Seyfert 1 galaxies (de Bruyn, 1980; Peterson et al., 1985, and references therein; Ulrich et al., 1984; Stirpe et al., 1988), with various intensities and at various time-scales. The strong, steady variation which Fairall 9 has been undergoing, however, is unique. It allows us to investigate the behaviour of other, weaker features of the spectrum, such as the strongest Fe II lines. Of particular importance are the lines of multiplet 42, which are located in the spectral region close to Hβ and the [O III] lines. An accurate measurement of the m 42 fluxes would be useful with respect to the [O III]-wing problem: like many other Seyfert 1 galaxies, Fairall 9 presents a strong, broad wing under the [O III] λ5007 line. Van Groningen and de Bruyn (1989, hereafter referred to as vGdB), who studied this feature in detail in this and in many other objects, suggested that the wing is due at least in part to broad [O III] emission from a region intermediate between the broad line region (BLR) and the narrow line region (NLR). Foltz et al. (1983) and Meyers and Peterson (1985) also interpreted this feature as a blend of Fe II lines and broad [O III] emission in Arakelian 120, as did Crenshaw and Peterson (1986) in a small sample of Seyfert 1 galaxies. The presence of a broad [O III] component is predicted by some models for the BLR, such as those suggested by Shields (1978) and Mathews (1982). However, the broad [O III]-wing observed by us and vGdB is most likely emitted from a region well outside the BLR, as discussed below.

One of the major uncertainties in the interpretation of the [O III]-wing is the fact that up to now no absolutely safe upper limit could be set on the flux of Fe II λ5018, which also contributes to the wing. An indication can be obtained from Fe II λ5169, another line from multiplet 42, if one assumes a ratio of 1:1 between the two lines. This is the expected value under optically thick conditions: however no solid observational confirmation of this existed. In vGdB an extensive analysis is performed for a sample of Seyfert 1 galaxies, by subtracting a template of equal strength from both wavelength locations and showing that a residual always remains under [O III] even when Fe II λ5169 (and therefore also λ5018) has been completely subtracted. Furthermore, vGdB also rule out several other lines.

In this paper we present a new spectrum of Fairall 9, taken in early 1987, 4 years after the one published in vGdB. At the later epoch the Balmer lines were much weaker, although the luminosity, after its long drop between 1978 and 1984, had by then passed its minimum state and was increasing. We will show that the Fe II lines have also decreased in flux, and that the decrease is the same for the two lines of m 42. But, most importantly, the larger part of the observed wing under [O III] λ5007 has the same intensity in the two spectra. This important observation enables us to draw a definite confirmation of the existence of broad [O III] emission.

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* Partly based on observations collected at the European Southern Observatory, La Silla, Chile

1989A&A...211..310S

2. Observations and reduction

The two spectra were taken in September-October 1982 with the 2.5 m Dupont telescope at the observatory of Las Campanas (Chile) using the photon-counting Reticon spectrometer, and on 11 January 1987 with the ESO/MPI 2.2 m telescope at the European Southern Observatory on La Silla (Chile). For a description of the observations and reduction of the first spectrum see vGdB (see also van Groningen, 1984). The second spectrum is the sum of two separate exposures of 30 min each, obtained with a RCA CCD attached to the Boller and Chivens spectrograph. The individual frames were reduced in the standard way (subtraction of bias, flat-fielding with a tungsten lamp, extraction with the Horne (1986) algorithm, wavelength calibration with a He/Ar lamp), co-added and calibrated with the standard star Hiltner 600, using the fluxes published by Stone (1977). Judging from the strength of the [O III] lines in other published spectra, we consider the absolute calibration to have an accuracy of about 30%. A slitwidth of 2″ was used, which approximately matched the seeing profile. The resolution obtained is 3 Å.

The 1982 spectrum was scaled to the 1987 one using the internal calibration based on the flux of the narrow lines. From an examination of the spatial distribution on the CCD frames we can exclude that the NLR is spatially resolved (the spatial resolution is 2″), and trust that the internal calibration is applicable. With this method an accuracy of 5% can be obtained if no strong extended narrow line region is present and the narrow lines are sufficiently strong (cf. Stirpe et al., 1988). The two spectra are shown in Fig. 1.

After the internal calibration, the continuum of Fairall 9 appears to be 30% stronger in the 1987 spectrum than in 1982. This could be due to the combination of effects given by the use of different apertures (a 2″ × 2″ square aperture in 1982, a 2″ wide slit in 1987), by different values of the seeing, and by different methods of extraction of the spectra. This last point could be particularly delicate, since extracting the spectrum with the Horne (1986) algorithm, the method used for the 1987 data, will cause a slightly higher contribution of the galactic emission to the spectrum. There are, however, some indications that the observed increase in the continuum is a real one. The light curves published by Glass (1986), and more recent photometric data by de Ruiter (personal communication) and Clavel et al. (1988) show that the luminosity of Fairall 9 reached a minimum at the end of 1984, and has been steadily rising since. Furthermore, an inspection of the spatial distribution of the CCD spectra shows that the galactic continuum accounts for 15% at most of the total continuum, providing a further indication that the difference between the two spectra is genuine.

3. Discussion

We have subtracted a power-law continuum from both spectra, fitting it to the intervals around 4210 Å and 5110 Å in the 1982 spectrum. As discussed by van Groningen (1984), these are the points where the true continuum is most likely to be reached, or closely approximated. For the 1987 spectrum the choice of a continuum is more difficult, because of the limited wavelength range. However, the fit to the 1982 spectrum shows that the interval around 4460 Å also comes very close to the continuum. We have therefore used this interval to fit the 1987 spectrum, as well as the same 5110 Å interval utilized in the 1982 fit. The slopes of the fitted power-laws are $\alpha = 1.18$ in 1982 and $\alpha = 0.35$ in 1987 (with $F_\nu \propto \nu^{-\alpha}$), but uncertainties of ± 0.4 cannot be excluded.

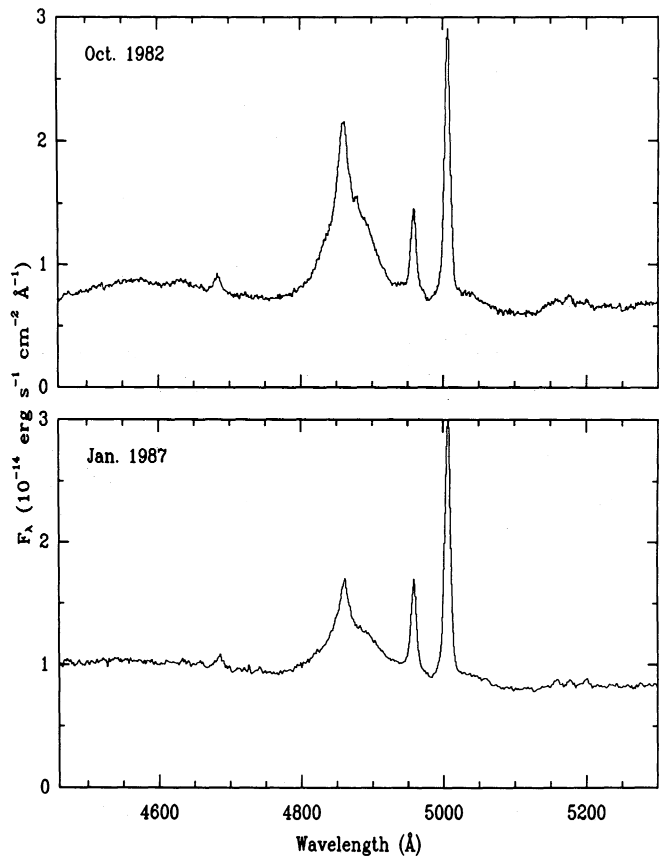

Fig. 1. Spectra of the Hβ region in Fairall 9, taken at the given dates. The 1982 spectrum has been scaled to the 1987 one on the basis of the [O III] λ5007 flux. The wavelength scales have been shifted to the rest-system of the galaxy ($z = 0.04612$), and both spectra have been rebinned in 1 Å intervals

Table 1. Ratios of the main line fluxes to [O III] λ5007 (F([O III] λ5007) $= 2.18\ 10^{-13}$ erg s^{-1} cm^{-2})

Line	1982	1987
Fe II (m37+m38)	1.59	0.45
Hβ (broad)	4.40	2.52
Hβ (narrow)	0.10	0.10
[O III]-wing [a]	0.13	0.12
Fe II λ5169	0.30	0.15
[Fe VII] λ5158	0.04	0.03
[Fe VI] λ5177	0.03	0.02
[N I] λ5200	0.04	0.05

[a] After subtraction of Fe II λ5018

The continuum subtracted spectra and their difference are shown in Fig. 2. The variation of the Fe II lines is clearly visible in the difference spectrum, not only in multiplet 42, but also in the stronger multiplets 37 and 38 on the blue side of Hβ, between 4450 Å and 4460 Å. The apparent lack of variation in multiplets 48 and 49 (at $\lambda > 5200$ Å) is probably due to the uncertainties in the continuum slopes. Table 1 resumes the line fluxes of the principal emission lines at both epochs.

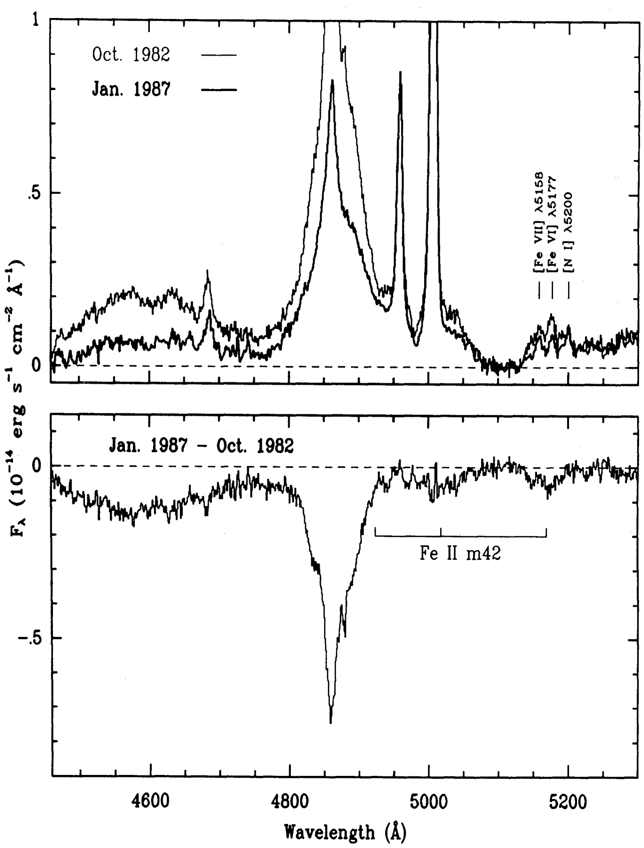

Fig. 2. Top: the two spectra shown in Fig. 1, after subtraction of a power-law continuum. The positions of the narrow lines which contaminate Fe II λ5169 are shown. Bottom: the difference between the two continuum-subtracted spectra. The positions of Fe II λ4924, λ5018 and λ5169 (multiplet 42) are indicated in the difference spectrum

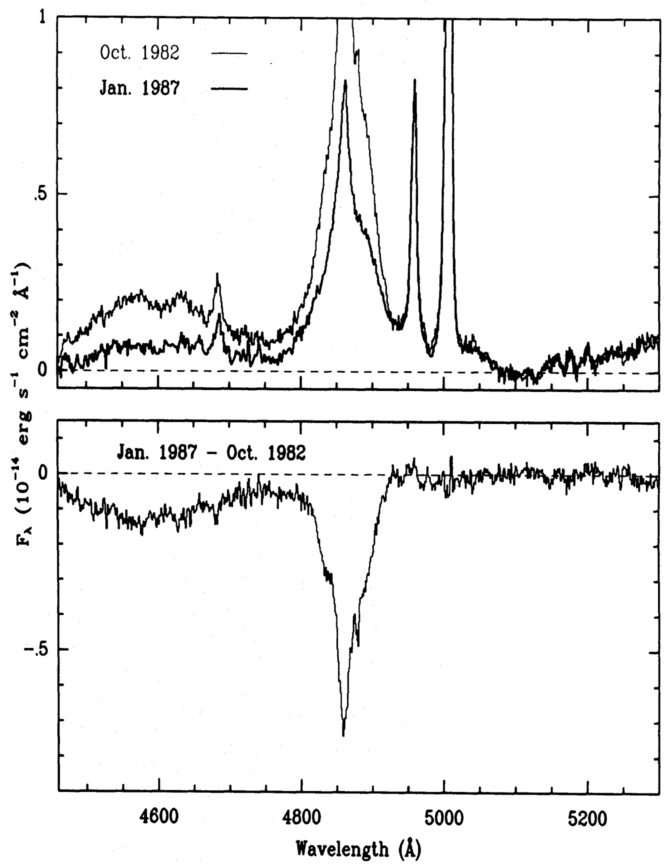

Fig. 3. Same as Fig. 2, after subtraction of the multiplet 42 lines (see text for details)

The most prominent feature of the difference spectrum is the decrease by about 50% of the flux in Hβ. Also evident are two bumps, at locations consistent with a variation of Fe II λ5018 and λ5169. We expect Fe II λ4924 (the third line of multiplet 42, which has the same strength as the other two) to be also present in the difference spectrum, but it is drowned by Hβ. Thanks to the very high signal-to-noise ratios of the spectra, there is no doubt as to the reality of the two Fe II features: to our knowledge, this is the first unquestionable detection of a variation of individual Fe II lines.

A very important fact emerges by examining the two individual spectra. While Fe II λ5169 is very weak in the later spectrum, *there is still a very strong emission under* [O III] λ5007. This is not the case in the first spectrum, where both features had comparable, and higher, strength. Notice that most of the remaining emission around 5170 Å in the 1987 spectrum is likely to be due to [Fe VII] λ5158 and [Fe VI] λ5177, which are clearly visible in both spectra, and possibly also to [Fe VI] λ5146.

As we can see from the difference spectrum, the two Fe II lines have decreased by a comparable amount, equal to 50 ± 20%. This important result strongly supports one of the basic assumptions of vGdB, namely that the line ratios in m42 are close to unity. There is in fact no reason to believe that this ratio would be different in the individual spectra. This makes it very difficult to interpret the [O III]-wing as Fe II m42 alone. We are thus faced with the best evidence up to now that some other broad feature is present under [O III] λ5007. Another important observation is that this feature has the same intensity in both spectra, contrary to all the other visible broad lines. This suggests that it has not varied during the 4 years separating the observations, and is therefore emitted from a much larger region than the BLR (>1 pc).

We have analysed the strengths of the lines in multiplet 42 (Fe II λ4924, λ5018, and λ5169) by using a template of Hα, from a spectrum obtained one day after the 1987 Hβ spectrum. The fact that the broad lines have not undergone major profile changes justifies the use of a 1987 Hα template for the 1982 spectrum. Using this template, we subtracted the three Fe II lines with equal intensities from the difference spectrum (Fig. 3, lower panel). This results in a perfectly flat spectrum, which confirms that the two bumps are really Fe II emission. The same template was subtracted from the same locations in the individual spectra, using scaling factors consistent with those of the difference spectrum, and with a 2:1 ratio between the ones used for 1982 and 1987 respectively. The ratios of Fe II λ5169 to Hβ are 0.07 and 0.06 (cf. Table 1).

The individual scaling factors were chosen on the basis of the strength of Fe II λ5169. The latter is contaminated by the [Fe VI] and [Fe VII] lines, and by [N I] λ5200. The narrow width of these lines allows nevertheless a good determination of the strength of Fe II λ5169. We can also exclude an artificial weakening of Fe II λ5169 by the Mg I b triplet, present in absorption in the stellar

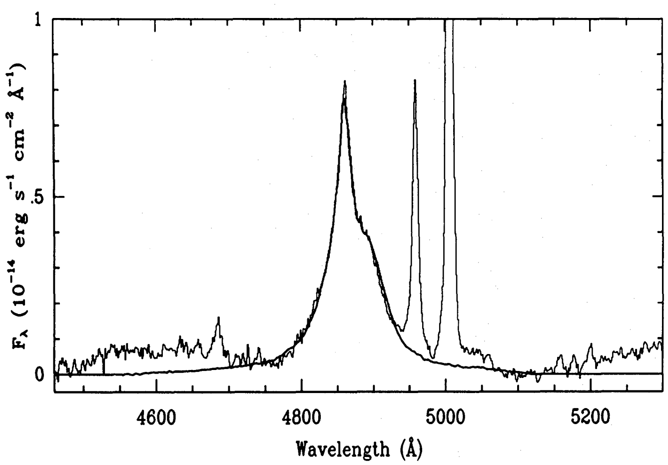

Fig. 4. The 1987 Hβ spectrum (thin line), shown as in Fig. 3. The thick line is a profile of Hα from the same epoch. The latter has been scaled in height and width, and cleansed from the blending lines, with the exception of its own narrow component. This direct comparison between the Hα and Hβ profiles allows us to exclude that the [O III]-wing is high-velocity Hβ emission, since no counterpart to it is visible in Hα

spectrum of the galaxy. The nucleus of this source is in fact too luminous with respect to the underlying galaxy for these lines to be important.

Having excluded Fe II λ5169 as the main contributor to the [O III]-wing, we now consider and rule out several other possibilities that the wing may *not* be λ5007 emission. Firstly, there are Fe II lines belonging to other multiplets, m36 in particular, which may be present very close to [O III] λ5007 (Joly, 1988). If they were so strong to produce the [O III]-wing, however, their behaviour would be very different from that of all the other visible Fe II lines, i.e. they would not have varied at all while all other lines have decreased by a factor 2. This is very unlikely, and therefore we exclude this possibility. For a detailed discussion of other possible broad line contributions see vGdB. Another possibility we can confidently exclude is that the [O III]-wing is a high-velocity wing of Hβ. Figure 4 shows the 1987 spectrum (after subtraction of continuum and m42 lines), upon which the corresponding Hα profile is superposed, scaled in height and width in order to match Hβ as closely as possible. Clearly, there is no counterpart to the [O III]-wing in Hα. Also the fact that spectrum drops below the level of the wing between [O III] λ4959 and λ5007 strongly argues against the wing being Hβ emission.

We therefore conclude that the wing on the red side of [O III] λ5007 is produced by high velocity forbidden line emitting material. The fact that there has been no variation in the [O III]-wing strongly supports the hypothesis advanced in vGdB that this emission is produced in a zone larger and more distant from the central source than the BLR. The time-interval between the two spectra indicates that this zone (defined in vGdB as TLR: Transition Line Region) has a radius greater than 1 pc.

Other remarkable facts emerge from the spectra of Fairall 9, which we will briefly examine in the remainder of this section.

Firstly, Hβ appears narrower in the difference spectra than in the individual ones: the width at 20% of the peak is $\sim$5000 km s^{-1} in the former against $\geqq$6500 km s^{-1} in the latter. This means that the wings of Hβ have equal intensity in the two spectra. The S/N ratio of our spectra is high enough to exclude that an eventual difference between the low-flux wings would be hidden by the noise, and furthermore the line falls off with a steeper gradient in the difference spectrum. The same phenomenon is observed also in NGC 5548 (Stirpe et al., 1988). There could be two possible explanations for this, providing that the higher velocities occur closer to the central mass. One is that the inner part of the BLR is matter-bound, and therefore less sensitive than the rest of the BLR to variations in the continuum. The other is that the inner region had already completely reacted to the increasing continuum in January 1987, while the rest of the line-emitting gas was still "seeing" a lower continuum due to light-travel delays. Similar effects are observed in recent unpublished spectra of NGC 5548, taken on time-scales of a few weeks. This favours the first explanation, since in that case the continuum exhibited a monotonic variation, and therefore no opposite reactions could have occurred in the line wings.

Another feature in the Hβ difference is the narrow component superposed on the main body of the line. Attention was drawn to this feature by van Groningen (1984), who first noticed that it is broader than the narrow lines, and is therefore not likely to be produced in the NLR. This is now confirmed by the fact that it appears in the difference spectrum, and has therefore undergone a variation. The FWHM of the feature in the difference spectrum is $\sim$1000 km s^{-1}, consistent with the value of 1100 km s^{-1} obtained by van Groningen (1984) from the deblended Hβ profile. The peak velocity of this narrow feature does not coincide with that of the narrow line, but is blue-shifted with respect to it by about 200 km s^{-1}. Its strength is comparable to the whole narrow spike in the 1987 spectrum.

Another, narrower, spike at $\sim$1200 km s^{-1}, visible in the 1982 spectrum, has disappeared in the 1987 one. Its FWHM is $\sim$250 km s^{-1}. The reality of this feature in the first spectrum is confirmed by the fact that it is visible also in Hγ and Hδ (van Groningen, 1984). This component reminds us of the ones observed by Ulrich et al. (1985) close to C IV λ1550 in NGC 4151, and which are interpreted as the products of two SS 433-like jets. However, the width of the Fairall 9 spike is smaller, and its velocity lower than that of the NGC 4151 features, and no counterpart is visible on the blue side. Attention should be paid in any future high resolution observations of this source, to see if the spike reappears, and if its velocity remains constant (as in the case of NGC 4151).

4. Conclusions

We have used the variability of Fairall 9 to demonstrate beyond reasonable doubt that the broad feature observed under [O III] λ5007 is only for a minor part due to Fe II λ5018. The bulk of this emission must therefore be due to [O III] emission. This [O III] component appears to have maintained the same intensity on a time scale of several years, suggesting that it is emitted from a region with radius $>$1 pc, as predicted by vGdB.

The variation of the broad Hβ profile suggests that the matter in the inner part of the BLR may be fully ionized, and does not therefore react to a continuum variation. Furthermore, we have shown that narrow, variable features are visible in the 1982 Hβ spectrum, but not in the 1987 one. They might have been produced by jets. This interpretation should however be considered with caution, and needs further observational evidence to be confirmed.

Acknowledgements. We are grateful to Dr. H.R. de Ruiter for allowing us to inspect his photometric data in advance of publication. GMS acknowledges support from the Netherlands

Foundation for Astronomical Research (ASTRON), with financial aid by the Netherlands Organization for Scientific Research (NWO).

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