The UV radiation from $z \sim 2.5$ radio galaxies: Keck spectropolarimetry of 4C 23.56 and 4C 00.54

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ABSTRACT

We present the results of deep spectropolarimetry of two powerful radio galaxies at \( z \sim 2.5 \) (4C 00.54 and 4C 23.56) obtained with the W.M. Keck II 10m telescope, aimed at studying the relative contribution of the stellar and non-stellar components to the ultraviolet continuum. Both galaxies show strong linear polarization of the continuum between rest-frame \( \sim 1300-2000 \) Å, and the orientation of the electric vector is perpendicular to the main axis of the UV continuum. In this sense, our objects are like most 3C radio galaxies at \( z \sim 1 \).

The total flux spectra of 4C 00.54 and 4C 23.56 do not show the strong P-Cygni absorption features or the photospheric absorption lines expected when the UV continuum is dominated by young and massive stars. The only features detected can be ascribed to interstellar absorptions by SiII, CII and OI. Our results are similar to those for 3C radio galaxies at lower \( z \), suggesting that the UV continuum of powerful radio galaxies at \( z \sim 2.5 \) is still dominated by non-stellar radiation, and that young massive stars do not contribute more than \( \approx 50\% \) to the total continuum flux at 1500 Å.

Subject headings: galaxies: active – galaxies: individual: (4C23.56,4C00.54) – polarization– quasars: general – ultraviolet: galaxies – radio continuum: galaxies – scattering
1. Introduction

High-z radio galaxies (HzRGs) are observable to very high redshifts and can be used to study the formation and evolution of massive elliptical galaxies (see McCarthy 1993 for a review). One of the most controversial issues is the physical cause of the alignment between the radio source and UV continuum axes of the HzRGs (the so called ‘alignment effect’, Chambers, Miley & van Breugel 1987, McCarthy et al. 1987). Two main competing scenarios have been proposed. The first is star formation induced by the propagation of the radio source through the ambient gas (see McCarthy 1993 and references therein); the second explains the alignment effect as the result of a hidden quasar whose radiation is emitted anisotropically and scattered towards the observer, producing strong linear polarization perpendicular to the radio-UV axis (Tadhunter et al. 1988; di Serego Alighieri et al. 1989). The latter scenario is closely related to the unification of powerful radio-loud AGN, and provides a way of testing it directly (see Antonucci 1993 and references therein). After the first detections of strong UV polarization in HzRGs obtained with 4m-class telescopes (di Serego Alighieri et al. 1989; Jannuzi & Elston 1991; Tadhunter et al. 1992; Cimatti et al. 1993), recent observations made with the Keck I 10m telescope have demonstrated the presence of spatially extended UV continuum polarization and of hidden quasar nuclei in some of the 3C radio galaxies at $0.7 < z < 1.8$, favoring the beaming and scattering scenario (Cohen et al. 1996; Cimatti et al. 1996,1997; Dey et al. 1996; Tran et al. 1998). On the other hand, Dey et al. (1997) have recently shown that the UV continuum of 4C 41.17 ($z = 3.8$) is unpolarized and consistent with that of a typical starburst galaxy. The most stringent comparison between the starburst and the scattering scenarios can be performed at $\lambda_{\text{rest}} \sim 1000 - 2000$ Å, where most of the strongest spectral features of O and B stars are located. This spectral window can be covered from the ground by observing radio galaxies at $z > 2$. We have started a program of observations of these galaxies using spectropolarimetry at the Keck II 10m telescope, and in this Letter we report on the
first two objects we have studied, concentrating on their continuum and absorption line properties. Throughout this paper we assume $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0$.

2. Observations and analysis

The observations were made on UT 1997 July 5-7 with the Keck II 10m telescope equipped with the instrument LRIS (Low Resolution Imaging Spectrometer; Oke et al. 1995) and its polarimeter (Goodrich et al. 1995). The LRIS detector is a Tek 2048$^2$ CCD with 24$\mu$m pixels which correspond to a scale of 0.214 arcsec pix$^{-1}$. We used a 300 line/mm grating and a 1.5 arcsecond wide slit, providing a dispersion of 2.4 Å/pixel. The spectral resolution, measured from sky and HgKr lamp lines, is $\approx 13$ Å (FWHM). The seeing ranged from about 0.5 to 1.0 arcseconds. Polarized (VI Cygni 12) and unpolarized/spectrophotometric (BD+33$^\circ$2642) standard stars (Schmidt, Elston & Lupie 1992) were observed in order to check and calibrate the polarimeter and to flux calibrate the spectra of the radio galaxies. Details on the observation technique and on the data reduction can be found in recent papers (Cimatti et al. 1996; Dey et al. 1996; Cohen et al. 1997). The statistical errors on $P$ and $\theta$ have been treated following the method outlined by Fosbury, Cimatti & di Serego Alighieri (1993) and developed by Vernet et al. (in preparation).

We observed 4C 23.56 ($z = 2.482$; Knopp & Chambers 1997) and 4C 00.54 ($z = 2.366$; Röttgering et al. 1997). These galaxies were selected to have $\text{Ly}\alpha$ redshifted to $\lambda > 4000$ Å and to be observable continuously for several hours. 4C 23.56 was observed with the slit oriented at P.A.$=47^\circ$ in one set $4 \times 1800$ seconds + one set $(1800+1626+1320+1320)$ seconds + one set $(2700+3 \times 2100)$ seconds, corresponding to a total integration time of about 6.2 hours. 4C 00.54 was observed with the slit oriented at P.A.$=134^\circ$ in one set $4 \times 1800$ seconds + one set $4 \times 2280$ seconds (i.e. about 4.5 hours). 4C 23.56 has two main components separated by about 5 arcseconds (called $a$ and $b$); both have strong $\text{Ly}\alpha$.
emission, but most of the continuum emission comes from the south-west region (component a) (Knopp & Chambers 1997). The spectra of 4C 00.54 and 4C 23.56\(b\) were extracted with an aperture of 19 pixels (4.1 arcsec), whereas an aperture of 23 pixels (4.9 arcsec) was used for 4C 23.56\(a\). Since the nights were not photometric, the spectra have been scaled to the published \(R\)-band magnitudes of the two galaxies (Knopp & Chambers 1997; Röttgering et al. 1997). The spectra were finally dereddened for Galactic extinction using the Burnstein & Heiles (1982) maps, which provided \(E_{B-V} = 0.16\) and \(E_{B-V} = 0.02\) for 4C 23.56 and 4C 00.54 respectively, and adopting the extinction curve of Cardelli, Clayton & Mathis (1989).

3. Results

The results of spectropolarimetry are displayed in Figures 1,2,3. Both galaxies show linearly polarized UV continuum. The degree of polarization rises into the blue for 4C 23.56\(a\). For 4C 23.56\(b\) (Fig. 2) we derive an upper limit of \(P_{3\sigma} < 6.9\%\) in the range \(\lambda_{\text{obs}} = 4266-7000\ \text{Å}\). The signal-to-noise ratio for 4C 00.54 is lower, but we detect significant polarization in the bluest part of the spectrum, with \(P = 11.9 \pm 2.6\%\) and \(P = 13.1 \pm 2.3\%\) at \(\Delta\lambda_{\text{obs}} = 4199-4667\ \text{Å}\) and 4745-5160 \(\text{Å}\) respectively. If we define two wide bins, we still measure significant polarization \((P = 8.9 \pm 1.1\%\) and \(P = 4.2 \pm 1.3\%\) at \(\Delta\lambda_{\text{obs}} = 4199-5495\ \text{Å}\) and 5627-7500 \(\text{Å}\) respectively), suggesting an increase of \(P(\lambda)\) into the blue also for this galaxy. The position angle of the electric vector (\(\theta\)) is approximately perpendicular to the main axis of the UV continuum of both galaxies (4C 23.56\(a\): P.A.\(\cdot\text{UV cont.} \sim 90^\circ\); Knopp & Chambers 1997; 4C 00.54: P.A.\(\cdot\text{UV cont.} \sim 0^\circ\); H. Röttgering, personal communication).

Table 1 shows the properties of the emission lines in the total flux spectra, but the signal-to-noise ratio of the present data is insufficient to reach a definitive conclusion about their polarization. For 4C 23.56\(a\) we derive the continuum-subtracted degree of polarization of the strongest emission lines: \(P_{3\sigma}(\text{Ly}\alpha) < 5.0\%\) and \(P_{3\sigma} (\text{CIV}) < 8.0\%.\) For 4C 00.54 we
obtain $P_{3\sigma}(\text{CIV})< 9.5\%$, whereas we detect a formally significant polarization for the Ly$\alpha$ line ($P=6.0\pm0.7\%, \theta = 30^\circ \pm 2.5^\circ$). However, we do not regard this Ly$\alpha$ polarization as real because the line is heavily affected by cosmic ray residuals.

We searched for the spectral signatures of young massive stars, by looking for P-Cygni profiles (in the lines NV$\lambda 1240$, OV$\lambda 1371$, SiIV$\lambda 1400$, CIV$\lambda 1549$, HeII$\lambda 1640$, NIV$\lambda 1719$) and for unambiguously photospheric absorption lines not affected by nearby emission lines (such as SiIII$\lambda 1296$, SiIII$\lambda 1417$, CIII$\lambda 1428$, S$\lambda 1502$). We compared our spectra to that of the starburst region B1 in the nearby star-forming galaxy NGC 1741 (Conti, Leitherer & Vacca 1996), and we also searched using the line lists of Kinney et al. (1993). No clear evidence was found for any of the P-Cygni absorptions (see Figures 4 and 5). For the photospheric absorptions, after taking into account the spectral resolution, we obtain the most stringent limits for SiIII$\lambda 1296$ and S$\lambda 1502$, where for both lines we obtain $W_{\lambda}(\text{rest})< 0.6$ Å in 4C 23.56a and $W_{\lambda}(\text{rest})< 0.7$ Å in 4C 00.54. In comparison, NGC 1741B1 has $W_{\lambda} \sim 0.6$ Å for both lines (Conti et al. 1996), and 4C 41.17 has $W_{\lambda}(\text{rest})(\text{SiIII}1296)=0.8\pm0.2$ Å and $W_{\lambda}(\text{rest})(\text{S}1502)=0.4\pm0.1$ Å (Dey et al. 1997). Only for 4C 00.54 do we tentatively detect an absorption line: CIII$\lambda 1428$ ($W_{\lambda}(\text{rest})=0.6$ Å, Figure 5), whereas the same line has $W_{\lambda}(\text{rest})< 0.6$ Å in 4C 23.56a. The CIII$\lambda 1428$ line is observed typically in O stars (Kinney et al. 1993) and it has $W_{\lambda} \sim 0.5$ Å in NGC 1741B1 (Conti et al. 1996). However, because of the lack of other strong O star features in the spectrum of 4C 00.54, we regard the detection of the CIII$\lambda 1428$ line as uncertain. The only clear and significantly detected absorption lines are Si II$\lambda 1260$, Si II+OI$\lambda 1303$, C II$\lambda 1335$, and Si II$\lambda 1526$ (Fig. 4 and 5, Table 2). These lines are generally ascribed to interstellar absorption (Kinney et al. 1993; Sahu & Blades 1997). Their rest-frame equivalent widths (typically 1-2 Å) are, within the errors, similar to those detected in 4C 41.17, i.e. larger than the Galactic values (Kinney et al. 1993), but somewhat smaller than the typical values observed in nearby starburst galaxies ($\sim 2$ Å; Conti et al. 1996).
4. Discussion

Our observations suggest that the UV spectra of 4C 23.56 and 4C 00.54 are not dominated by young massive stars, whereas the strong perpendicular polarization indicates the presence of a relevant scattered continuum, making 4C 23.56 and 4C 00.54 similar to the polarized 3C radio galaxies at 0.7< z <2. Adopting the prescriptions of Dickson et al. (1995) and Manzini & di Serego Alighieri (1996) and assuming the average HeII$\lambda$1640/H$\beta$ ratio (3.18) observed in radio galaxies (McCarthy 1993), we estimate that the nebular continuum contributes only $\sim$8% and $\sim$13% to the total flux at 1500 $\AA$ for 4C 23.56a and 4C 00.54 respectively.

If we assume that all HzRGs have an obscured quasar nucleus which feeds the powerful radio source and whose light is scattered by dust and/or electrons, we can interpret the low (or null) polarization of 4C 41.17 (Dey et al. 1997) as due to dilution of the scattered radiation by the unpolarized light of young stars. A limit on the amount of stellar light in the UV continuum of 4C 23.56a and 4C 00.54 can be derived by assuming that the observed polarization is diluted by the unpolarized stellar and nebular continua. The ratio between the stellar light and the total flux at 1500 $\AA$ can be roughly estimated as $F_{stars}/F_{total} = \{[1 - (P_{obs}/P_{0})] - \kappa\}$, where $P_{obs}$ and $P_{0}$ are the observed and intrinsic degree of polarization and $\kappa$ is the ratio between the nebular and the total continuum. Adopting a half-cone opening angle of 45$^\circ$ and an angle of 90$^\circ$ between the cone axis and the line of sight, we derive $P_{0}$ $\sim$30% and $P_{0}$ $\sim$50% for dust (Manzini & di Serego Alighieri 1996) and electron scattering (Miller, Goodrich & Mathews 1991) respectively. Thus, adopting $P_{obs}(1500 \text{ } \AA)$=13.1% and 14.4% for 4C 00.54 and 4c 23.56a respectively, for dust scattering we obtain that $F_{stars}/F_{total} \leq 43\%$ and $\leq 44\%$ for 4C 00.54 and 4C 23.56a respectively, whereas $F_{stars}/F_{total}$ increases to $\leq 61\%$ and $\leq 63\%$ for electron scattering. These ratios can be considered upper limits because we do not know if the observed scattered light is really
diluted by a stellar continuum, and they imply that stellar light cannot contribute more than about half of the UV continuum at 1500 Å.

The properties of 4C 23.56, 4C 00.54 and 4C 41.17 can be interpreted in a evolutionary scenario where HzRGs at $z > 3$ have a major episode of star formation, and their AGN scattered component is diluted by the stellar light, but it becomes observable at lower $z$ when the starburst ceases. However, given the rapid evolution of the UV light from a starburst, it is also possible that 4C 41.17 simply represents a case dominated by the starburst rather than an evolutionary sequence. Future observation of a complete sample of HzRGs will help us to understand the nature of the alignment effect and the evolution of the host galaxies of powerful radio sources.

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REFERENCES

Antonucci, R. 1993, ARA&A, 31, 473.

Burnstein, D., Heiles, C 1982, AJ, 87, 1167

Cardelli, J.A., Clayton, G.C., Mathis, J.S. 1989, ApJ, 345, 245

Chambers K.C., Miley G.K., van Breugel W. 1987, Nature, 329, 604

Cimatti, A., di Serego Alighieri, S., Fosbury, R. A. E., Salvati, M., & Taylor, D. 1993, MNRAS, 264, 421

Cimatti A., Dey A., van Breugel W., Antonucci R., Spinrad H. 1996, ApJ, 465, 145

Cimatti A., Dey A., van Breugel W., Hurt T., Antonucci R. 1997, ApJ, 476, 677

Cohen M.H., Tran H.D., Ogle P.M., Goodrich R.W. 1996, in Proceedings of the IAU Symposium 175 on "Extragalactic Radio Sources", Fanti et al. eds., Kluwer, p. 223

Cohen M.H., Vermeulen R.C., Ogle P.M., Tran H.D. 1997, ApJ, 484, 193

Conti, P.S., Leitherer, C., Vacca, W.D. 1996, ApJ, 461, L87

Dey A., Cimatti A., van Breugel W., Antonucci R., Spinrad H. 1996, ApJ, 465, 157

Dey A., van Breugel W., Vacca W., Antonucci R. 1997, ApJ, 490, 698

di Serego Alighieri S., Fosbury R.A.E., Quinn P.J., Tadhunter C.N. 1989, Nature, 341, 307

Dickson, R., Tadhunter, C., Shaw, M., Clark, N., Morganti, R. 1995, MNRAS, 273, L29

Fosbury, R.A.E., Cimatti, A., di Serego Alighieri, S. 1993, The Messenger, 74, 11.

Goodrich R., Cohen M.H., Putney 1995, PASP, 107, 179
Jannuzi, B.T., Elston, R. 1991, ApJ, 366, L69

Kinney A.L., Bohlin R.C., Calzetti D., Panagia N., Wyse R. 1993, ApJS, 86, 5

Knopp G.P., Chambers K.C. 1997, ApJS, 109, 367

Manzini A., di Serego Alighieri S. 1996, A&A, 311, 79

McCarthy P.J., van Breugel W., Spinrad H., Djorgovski S. 1987, ApJ, 321, L29

McCarthy P.J. 1993, ARA&A, 31, 693

Miller, J.S., Goodrich, R.W., Mathews, W.G. 1991, ApJ, 378, 47

Oke J.B., Cohen J.G., Carr M., Cromer J., Dingizian A., Harris F.H., Labrecque S., Lucino R., Schaal W., Epps H., Miller J. 1995, PASP, 107, 335

Röttgering H.J.A., van Ojik R., Miley G.K., Chambers K.C., van Breugel W.J.M., de Koff S. 1997, A&A, 326, 505

Sahu, M.S., Blades, J.C. 1997, ApJ, 484, L125

Schmidt, G.D., Elston, R., Lupie, O.L. 1992, AJ, 104, 1563

Tadhunter C.N., Fosbury R.A.E., di Serego Alighieri S. 1988, Proceedings ”BL Lac Objects”, ed. Maraschi L., Maccacaro T., Ulrich M.H., Springer-Verlag, p. 79

Tadhunter, C.N., Scarrott, S.M., Draper, P., Rolph, C., 1992, MNRAS, 256, 53p

Tran, H.D., Cohen, M.H., Ogle, P.M., Goodrich, R.W., di Serego Alighieri, S. 1998, ApJ, in press

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Fig. 1.— The spectral and polarization properties of 4C 23.56a. From top to bottom: the observed total flux spectrum, the percentage polarization, the position angle of the electric vector and the polarized flux spectrum. Filled circles and crosses indicate respectively continuum, and emission lines with their underlying continuum.
Fig. 2.— The spectral and polarization properties of 4C 23.56b (same symbols as Figure 1). No significant polarization is detected.
Fig. 3.— The spectral and polarization properties of 4C 00.54 (same symbols as Figure 1). The polarization of the Lyα line is an artifact due to cosmic ray residuals (see text).
Fig. 4.— Top panel. Bottom spectrum: 4C 23.56\(a\) corrected for Galactic extinction (the spectrum is smoothed with a 3 pixel boxcar). Top spectrum: the nearby starburst galaxy NGC 1741B1 scaled to the continuum of 4C 23.56\(a\) and offset by +5.5. Bottom panel. The spectrum of 4C 23.56\(a\) (bottom) compared to that of NGC 1741B1 (top, offset by +1.5).
Fig. 5.— *Top panel.* Bottom spectrum: 4C 00.54 corrected for Galactic extinction (the spectrum is smoothed with a 3 pixel boxcar). Top spectrum: the nearby starburst galaxy NGC 1741B1 scaled to the continuum of 4C 00.54 and offset by +5.0. *Bottom panel.* The spectrum of 4C 00.54 (bottom) compared to that of NGC 1741B1 (top, offset by +2.0).
Table 1. Emission Line Measurements

| Galaxy  | Line         | F/F(Lyα) | W_λ (obs) (Å) | FWHM (km s\(^{-1}\)) |
|---------|--------------|----------|---------------|----------------------|
| 4C 23.56a | Lyα         | 1.00     | 302           | 1458                 |
|         | NVλ1240     | 0.17     | 58            | 1914                 |
|         | SiIVλ1394   | 0.02     | 10            | 1400                 |
|         | SiIVλ1403   | 0.04     | 15            | 1200                 |
|         | CIVλ1549    | 0.26     | 77            | 1057                 |
|         | HeIIλ1640   | 0.19     | 72            | 1024                 |
|         | OIII\(λλ\)1658-1666 | 0.06 | 29            | 2089                 |
|         | CIII\(λ\)1908 | 0.16   | 66            | 1219                 |
|         | CIII\(λ\)2327 | 0.10 | 52            | 1607                 |
|         | [NeIV]\(λ\)2424 | 0.17 | 112           | 1954                 |
| 4C 23.56b | Lyα         | 1.00     | 2200          | 1565                 |
|         | NVλ1240     | 0.08     | 438           | 2916                 |
|         | CIVλ1549    | 0.17     | 299           | 1252                 |
|         | HeIIλ1640   | 0.14     | 254           | 972                  |
|         | CIII\(λ\)1908 | 0.08 | 160           | 922                  |
| 4C 00.54  | Lyα         | 1.0      | 1488          | 1466                 |
|         | NVλ1240     | 0.06     | 78            | 2156                 |
|         | SiIVλ1394   | 0.015    | 22            | 1867                 |
|         | SiIVλ1403   | 0.022    | 32            | 1460                 |
|         | CIVλ1549    | 0.12     | 139           | 1381                 |
|         | HeIIλ1640   | 0.09     | 129           | 1087                 |
|         | OIII\(λλ\)1658-1666 | 0.013 | 22            | 1284                 |
|         | CIII\(λ\)1908 | 0.04 | 74            | 1123                 |
|         | CIII\(λ\)2327 | 0.013 | 38            | 500                  |
|         | [NeIV]\(λ\)2424 | 0.08 | 216           | 2243                 |

\(^a\)Lyα fluxes: 8.0×10\(^{-16}\) erg s\(^{-1}\) cm\(^{-2}\) (4C 23.56a), 3.0×10\(^{-16}\) erg s\(^{-1}\) cm\(^{-2}\) (4C 23.56b), 2.8×10\(^{-15}\) erg s\(^{-1}\) cm\(^{-2}\) (4C 00.54). The fluxes are in the observed frame and dereddened using \(E_{B-V}=0.16\) (4C 23.56) and \(E_{B-V}=0.02\) (4C 00.54) (see text).
Table 2. Absorption Line Measurements

| Galaxy  | $\lambda_{\text{obs}}$ (Å) | $W_{\lambda}(\text{obs})$ (Å) | FWHM (km s$^{-1}$) | Identification         |
|---------|-----------------------------|-----------------------------|-------------------|------------------------|
| 4C 23.56a | 4400.0                      | 5.0±0.7                     | 648±136           | SiIIλ1260.4           |
|         | 4547.5                      | 5.5±0.6                     | 798±152           | OIλ1302.2+SiIIλ1304.4 |
|         | 4657.0                      | 8.0±0.8                     | 805±161           | CIIλ1335               |
|         | 5323.0                      | 3.0±0.5                     | 338±112           | SiIIλ1527              |
| 4C 00.54 | 4236.5                      | 3.0±0.5                     | 389±141           | SiIIλ1260.4           |
|         | 4379.3                      | 5.5±0.9                     | 959±198           | OIλ1302.2+SiIIλ1304.4 |
|         | 4799.0                      | 2.5±0.5                     | 281±94            | CIIIλ1428 ?            |