Keck spectropolarimetry of radio galaxies at $z \sim 2.5$

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Abstract. We present the preliminary results of deep Keck spectropolarimetry of two radio galaxies at $z \sim 2.5$. The UV continuum is highly polarized in both galaxies, and we do not see photospheric absorption lines due to O and B stars. In these two senses our objects are like most RG at $z \sim 1$, and they are unlike 4C41.17 at z=3.8 (Dey et al. 1997), which does show the O and B stars features and is not polarized.

1. Introduction

High-z radio galaxies (HzRG) are observable to very high redshifts, the most distant radio galaxy known being at $z \sim 4.4$ (Rawlings et al. 1996), and are spatially resolved in ground-based optical and near-IR observations. Since powerful radio sources have elliptical galaxy hosts in the local universe, HzRG can be used to investigate the evolution of massive galaxies at early epochs. In addition, HzRG appear to experience a 'dusty phase' (Hughes et al. 1997; Cimatti et al. 1998) that is expected in several scenarios of massive spheroidal galaxy evolution (Mazzei & De Zotti 1996 and references therein).

The physical cause of the alignment between the radio source and UV continuum axes (the so called 'alignment effect', Chambers, Miley & van Breugel 1987, McCarthy et al. 1987), is still controversial. 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 aligned UV continuum as the result of a hidden quasar nucleus 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 it provides a way of testing it directly.

Recent Keck observations have demonstrated the presence of spatially extended UV continuum polarization and of hidden quasar nuclei in some of the 3C radio galaxies at $0.7 < z < 1.8$, favouring the beaming and scattering scenario (Cohen et al. 1996; Cimatti et al. 1996, 1997; Dey et al. 1996). However, the spectral region typically covered by these observations ($\lambda_{rest} \sim 2000 - 4000$ Å) does not include easily identifiable signatures of massive young O and B stars, and therefore only indirect methods have been used to investigate the presence of a young stellar population (see for instance Cimatti et al. 1997). The best way to investigate the relative contributions of young stars and scattered light and the nature of the alignment effect is to observe HzRG with $z > 2$, in order to cover the rest-frame region $\lambda_{rest} \sim 1000 - 2000$ Å, where most of the strongest spectral features of O and B stars are present. Dey et al. (1997) have shown that the UV continuum of 4C 41.17 ($z = 3.8$) has properties different from those of 3C radio galaxies at $z \sim 1$, being unpolarized ($P_{2\sigma}$ <2.4%) and consistent with that of a typical starburst galaxy. However, this galaxy still shows an extended emission line region which requires an ionization mechanism other than the radiation field from the hot stars.

In order to investigate the generality of this result and to understand the nature of the alignment effect, we have recently started a program of Keck spectropolarimetry of HzRG with $z > 2.3$. Spectropolarimetry is important to obtain data on both the polarization and the spectral properties, and to test the validity of the unification model of AGN (see Antonucci 1993).

2. Observations

The typical magnitudes of powerful HzRG at z >2 are R >22, and the signal-to-noise ratio needed for spectropolarimetry can be reached only with 10m-class telescopes. Our first observations were made in July 1997 with the Keck II 10m telescope equipped with the instrument LRIS (Low Resolution Imaging Spectrometer; Oke et al. 1995). The observations cover the rest-frame spectral range $\sim 1000 - 2000$ Å and were made under good seeing conditions ($0.5 - 1.0$ arcsec). The spectropolarimeter is a dual beam instrument which uses a calcite analyser and a rotatable waveplate (Goodrich et al. 1995) . We used a 300 line/mm grating and a 1.5 arcsec wide slit. The LRIS detector is a Tek 2048^2 CCD with 24μm pixels which correspond to a scale of 0.214 arcsec pix^{-1}. The dispersion is $\approx$2.5 Å pix $^{-1}$. A complete observation includes 4 integrations made at four half-wave plate positions (0°, 45°, 22.°5, 67.°5). Unpolarized and polarized standard stars were observed in order to check and calibrate the instrumental polarization and the polarizance, and to calibrate the position angle zero point offset. The observations and data analysis are described in detail in several recent papers (Cimatti et al. 1996; Dey et al. 1996; Cohen et al. 1997).

The two sources described here are 4C 23.56 ($z = 2.48$) (Knopp & Chambers 1997) and 4C 00.54 ($z = 2.37$) (Röttgering et al. 1997). These galaxies have magnitudes $R \sim 22.5$ and were selected in order to have Lyα redshifted to $\lambda >$ 4000 Å (where the LRIS sensitivity is high) and to be observable continuously for several hours during our run. 4C 23.56 was observed for about 6.5 hours and

Figure 1. The spectral and polarization properties of 4C 23.56a. From top to bottom: the 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.

4C 00.54 for about 4.5 hours. 4C 23.56 has two main components (called a and b): both have strong Lyα emission but most of the continuum emission comes from the south-west region (component a) (Knopp & Chambers 1997).

3. Main results

4C 00.54 and 4C 23.56 show very similar properties and Figure 1 displays the results for 4C 23.56a. The main findings can be summarized as follows.

- The UV continuum is strongly polarized. The degree of polarization rises smoothly into the blue for 4C 23.56a, increasing from about 10% to about 20%. The continuum of the component 4C 23.56b is too faint to allow a meaningful measurement of the polarization, and we derive an upper limit at $\lambda_{rest} \sim 1300 - 1800$ Å of $P_{3\sigma} < 15\%$. The signal-to-noise ratio for 4C 00.54 is lower, but we detect significant polarization in the blue part of the spectrum with $P \sim 10 - 15\%$. The orientation of the electric vector in both 4C 23.56a and 4C 00.54 is perpendicular to the main axis of the UV continuum. Therefore, the continuum polarization properties of 4C 23.56 and 4C 00.54 are very similar to those of a significant fraction of 3C radio galaxies at $z \sim 1$, and they are consistent with beaming and scattering.

- Although both free electrons and dust particles are generally present in the ISM of HzRG, it is important to understand which are the dominant scattering particles. The models of dust scattering predict the presence of distinctive features in $P(\lambda)$, such as a peak around 2200 Å in the case of Galactic dust (Manzini & di Serego Alighieri 1996). However, we recall that the scattering properties of the astronomical dust grains are still not well determined even in our Galaxy (see Manzini & di Serego Alighieri 1996), and therefore the predictions of the dust scattering models should be used with due precaution. Although the spectral resolution of $P(\lambda)$ of the 4C 23.56a binned data is low, Figure 1 does not show clear dust features. However, because of the uncertainties mentioned above, this result cannot be taken as the proof that Thomson scattering dominates. Electron scattering would produce an intrinsically constant $P(\lambda)$, and therefore the observed blue $P(\lambda)$ of 4C 23.56a would require an additional unpolarized diluting component with a red spectrum.

- In the case of scattering of radiation from an obscured quasar nucleus, Lyα and CIVλ1549 are the strongest permitted lines anticipated in the polarized flux spectrum. The signal-to-noise ratio is insufficient to reach a definitive conclusion about the polarization of these lines. We notice, however, that the total flux spectrum shows that CIVλ1549 line has a broad base, consistent with the presence of a scattered quasar spectrum.

- The spectra of both galaxies look different from that of 4C 41.17 (Dey et al. 1997), since they do not show the spectral features characteristic of a young starburst stellar population (emission lines with P-Cygni profiles and unambiguously photospheric absorption lines).

- We have detected the following absorption lines : S IIλ 1260, Si II+OIλ1303, C IIλ1335, Si IIλ1526 (Fig. 2). These lines are generally ascribed to interstellar absorption (Kinney et al. 1993), but they can also be produced in the photospheres of B stars. Their rest-frame equivalent widths are in the range of 1.3-2.2 Å , larger than the Galactic values, but somewhat smaller than the typical values ($\sim$2 Å) observed in nearby starburst galaxies.

4. Discussion

All the recent deep Keck observations of HzRG (0.7< z <3.8) have provided new insights into the physical properties of these galaxies. What we know is based on a small and incomplete sample and general conclusions should be drawn with caution. However, our conclusions regarding the properties of the the UV continuum can be summarized as follows: *(a)* at 0.7< z <2.5 it is often, although not always, polarized and when it is, the E-vector is perpendicular, it sometimes shows broad polarized permitted emission lines in the extended light, there are generally no unambiguous indications of hot young stars and it has a significant contribution from the nebular continuum emission associated with the high ionization extended emission line region; *(b)* the very limited data at $z > 3.5$ show low or zero polarization and unambiguous signatures of a young stellar population. These observations raise two main questions: (1) what causes the differences between the HzRG at $z > 3.5$ and those at lower z and, (2) is the starburst observed in HzRG at $z > 3.5$ causally related to the AGN?

Figure 2. Bottom spectrum : 4C 23.56a (smoothed with a 3 pixel boxcar). Top spectrum : the nearby starburst galaxy NGC 1741 scaled to the continuum of 4C 23.56a and offset by +2.5.

First of all, all HzRG must have an AGN which feeds the powerful radio source. We recall here that 4C 41.17 and 4C 23.56 have very similar radio powers at 1.4 GHz in the rest-frame . Therefore, if AGN scattered light is not observed, it means that either the polarized light is strongly diluted by the unpolarized UV continuum of the young stars, or that the number density of the scatterers is not sufficient to produce observable scattered light. Dust grains are much more efficient scatterers per unit mass than electrons. One could imagine that HzRG at $z > 3.5$ are making the first generation of stars and that there is insufficient dust in the ISM available for scattering. However this may conflict with the sub-mm detection of large amounts of dust in some HzRG at $z > 2$ (including 4C 41.17 itself) depending on how this dust is distributed. The observations of 4C 41.17 demonstrate that vigorous star formation is occurring, but do not necessarily demostrate that the starburst is induced by the radio source. Neither the sub-mm continuum nor the optical spectropolarimetric observations of 4C 41.17 are able to constrain the spatial location of the dust thermal emission or the star formation.

Regardless of the cause of the starburst, if HzRG have a major episode of star formation at say $z > 3$, we can envisage a scenario where the scattered polarized AGN component is not detectable in the far-UV because of the dilution. When the starburst ceases and the stellar population ages, the dilution will decrease to reveal the polarized component observable at lower redshifts. One possibility is to make polarization observations of the very high redshift objects at a rest-frame wavelength around 3000 Å in the minimum between the emission from the young and old stellar populations.

The observation of a complete sample of HzRG 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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