3D Optical Spectroscopic Methods in Astronomy
ASP Conference Series, Vol. 71, 1995
G. Comte, M. Marcelin, eds.

A Detailed Study of High Redshift Radio Galaxies

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Abstract. We report on an ongoing survey of the extended line emission in high redshift radio galaxies, using a tunable Fabry-Perot etalon. Some results and suitable models are presented for individual sources.

1. Introduction

Studies of steep spectrum radio galaxies, conducted in the 1980's, often found these sources to be associated with extended emission line regions (EELR) having sizes up to several hundred kpc. McCarthy *et al.* (1987) and Chambers *et al.* (1987) undertook the first systematic study to find such EELR in subsamples of 3C and 4C radio sources, respectively. A close relationship was found between the radio power and the optical emission line luminosity. More surprisingly, however, was the strong alignment discovered between the axes of radio and optical line and continuum emission. The number of radio galaxies displaying this *alignment effect* rapidly increase with redshift. Two models for the EELR were proposed:

Model (a) The radio jet triggers star formation in the surrounding medium which then ionizes the gas that forms the EELR (McCarthy *et al.* 1987, Chambers *et al.* 1987).

Model (b) The EELR is excited by UV radiation anisotropically emitted by an active nucleus, preferentially ionizing gas along the axis of a thick torus, which in turn hides the nucleus from the observer (Fosbury 1985, van Breugel *et al.* 1986).

2. Observations

In order to investigate the origin of the EELR, and their role in the evolution of galaxies, we began a detailed study of the kinematics and morphology of these source at high spatial and spectral resolution. This observing problem is perfectly matched to the capabilities of a Fabry-Perot (FP) interferometer.

For the purpose of this investigation we acquired two FP etalons with spectral resolution of $\sim$400 km sec^{-1}, optimized for the expected width of the EELR lines, and operating from 320 to 480 nm and from 430 to 820 nm, respectively (Meisenheimer & Hippelein 1992). The etalons are used as tunable filters and placed in the parallel beam of the focal reducer, installed at the prime focus of

https://doi.org/10.1017/S0252921100022776 Published online by Cambridge University Press

the 3.5 m telescope on Calar Alto, Spain. The sources (see Table 1) were selected according to the following criteria:

- high redshift ($z \gtrsim 0.5$), since the well-aligned sources dominate beyond this distance;
- one of the strong emission lines, [OII]λ372.7 or Ly-α, must fall into the wavelength bands accessible to our etalons;
- the EELR must be large enough ($\gtrsim 5''$) to allow for an adequately resolved spatial analysis; and,
- the surface brightness should be sufficiently large ($\geq 10^{-20}$ W m^{-2} arcsec^{-2}).

Table 1. Radio Galaxy Sample

Name	z	Line Studied	Size of EELR
3C 34	0.69	[OII]	17"
3C 44	0.66	"	10"
3C 54	0.83	"	5"
3C 124	1.08	"	7"
3C 169.1	0.63	"	8"
3C 265	0.81	"	35"
3C 337	0.64	"	13"
3C 352	0.81	"	12"
3C 368	1.13	"	9"
3C 435A	0.47	"	16"
3C 441	0.71	"	6"
4C 41.17	3.80	Ly-α	13"
B2 0902	3.39	"	10"

A typical FP observation consisted of imaging the galaxy at 8-10 different wavelengths in intervals of ~0.8 nm, across the emission line profile. Integration times of up to 1 hour were required at each wavelength setting. In order to investigate the alignment of the stellar continuum, as claimed in model (a), line-free direct imaging with intermediate-band filters (FWHM~10 nm) were obtained directly blueward and redward of the emission line studied.

3. Results and Discussion

In the following we describe our results for a handful of these radio galaxies. Physical parameters are derived using $H_0 = 50$ km sec^{-1} Mpc^{-1} and $q_o = 0.2$.

3C 368 is a FR II radio source. Its EELR, as seen in [OII]λ372.7 emission, is double-lobed and perfectly aligned with the radio jet. Several scenarios have been proposed: Djorgovski *et al.* interpreted it as a merging galaxy, Chambers *et al.* as a starburst induced by the radio jet, and LeFèvre *et al.* as the result of gravitational lensing. A careful analysis, however, reveals that the southern lobe of the EELR consists of a conical structure that lags about 10 kpc behind the bow shock associated with the corresponding radio lobe. In contrast to photoionization models, this cone morphology is open toward the galaxy core. The northern lobe has a similar morphology but is slightly smaller. As with the morphology, the velocity structure is rather symmetrical with relative velocities of $\sim$200 km sec^{-1}. These results indicate that none of the above interpretations is correct, and led us to propose a new, self-consistent model for the EELR in 3C 368:

Model (c) The bowshock associated with the radio jet propagates with a speed of roughly 1000 km sec^{-1}, sweeping up and heating the ambient medium to temperatures of several 10^7 K, thereby compressing and accelerating this gas. Following the passage of the bowshock the gas is left behind in the region downstream of the shock, where it can cool to $\sim$20 000 K and become visible in optical emission lines such as [OII] 372.7 nm. Due to the low gas densities of a few 0.1 cm^3, the cooling process requires several 10^7 years, during which time the shockfront, as represented by the radio hot spots, advances by many tens of kpc (Meisenheimer and Hippelein 1992). This model not only directly explains the correlation between radio power and the power in the emission lines, but also the alignment between the radio axis and the major axis of the EELR.

3C 352 is also a FR II source. Its elongated EELR also shows a symmetrical morphology and velocity structure. Though it is not distinctly separable into two lobes, we may apply model (c). Because of the lower gas densities in its outer regions, the cooling times are too long and we see the [OII]λ372.7 line emission only in the denser regions near the center of the galaxy. In this case we observe a rather small EELR, concentrated at the center of the radio galaxy. A further contribution to the excitation of the EELR may also come from a central UV source (Hippelein and Meisenheimer 1992).

3C 265 has a rather different morphology. The overall extent of the radio source is $\sim$800 kpc. The associated EELR, with an elongation of $\sim$350 kpc, is morphologically and kinematically extremely complex, being composed of at least a half dozen distinct line emitting components. The continuum image consists of a non-elongated central source surrounded by a number of companions mostly devoid of coincident line emission.

3C 34 is similar to 3C 265 but on a somewhat smaller scale. The radio source extent is $\sim$390 kpc and the size of the EELR is $\sim$150 kpc. The velocity map displays at least three distinct components spanning $\sim$800 kms^{-1}. The symmetrical continuum image of the radio galaxy is situated in a rich cluster of about a dozen galactic companions.

3C 435A is yet another source distinguished by complex morphology and kinematics. Although the inner 5″ of the radio galaxy display a blue- to red-shifted signature of a radio jet, the remainder of the EELR is kinematically chaotic. An abrupt $\sim$-200 kms^{-1} break with this feature marks the onset of a further component, dominated by a second peak of [OII]λ372.7 emission. One

https://doi.org/10.1017/S0252921100022776 Published online by Cambridge University Press

side of this component is connected to the radio galaxy by a "bridge" of line emission, while the opposite side is characterized by a long, tail-like feature extending ~40kpc from this emission maxima. A continuum source at a similar redshift to 3C 435A lies near this second peak of line emission. For this kind of complex EELR we propose another model (Neeser *et al.*, 1994):

Model (d) A close, strong interaction with a companion galaxy exchanges material with the central radio galaxy, creating a complex morphology of bridges, tails and extended knots along the interaction axis. The passage of the companion through the halo of the host source shock heats and/or induces star formation in the supplied gas and the ambient medium, thus creating the observed EELR and its complex velocity structure. The interaction itself may also trigger the radio source of the central galaxy.

Although the alignment of the EELR with the radio source is confirmed in our investigation, most of the objects showed no evidence of a continuum alignment. Our line-free images generally show rather symmetrical host galaxies. It is likely that the apparent *continuum* alignment effect arises from emission line contamination in the broad-band images obtained in previous studies.

4. Conclusions

We observe essentially four different morphological types of EELR:

1. Large, well-aligned symmetrical objects with blue and redshifted lobes and large turbulence (e.g. 3C 368, 3C 352, 3C 124). These EELR are probably excited by the bow shock driven by the radio jet.

2. Compact objects with blue and redshifted components, not separable into lobes (e.g. 3C 54, 3C 356). Here either photoionization or shock models may apply.

3. Complex systems with multiple components and chaotic kinematics (e.g. 3C 34, 3C 265, 3C 435A, 3C 169.1, 3C 44), probably excited by galaxy-galaxy interactions.

4. The very extended Ly-α halos around the high redshift objects 4C 41.17 and B2 0902+34 showing the most extreme turbulence ($\sim$2000 kms^{-1}). In addition to the expansion of the radio source, ongoing accretion onto the newly formed galaxy may also play an important role.

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