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Letter to the Editor

Tracing jet–ISM interaction in young AGN: correlations between [O III] λ 5007 Å and 5-GHz emission

A. Labiano[1,2,3]

[1] Departamento de Astrofísica Molecular e Infrarroja, Instituto de Estructura de la Materia (CSIC), Madrid, Spain
e-mail: labiano@damir.iem.csic.es
[2] Kapteyn Astronomical Institute, Groningen 9700 AV, The Netherlands
[3] Department of Physics, Rochester Institute of Technology, Rochester, NY 14623, USA

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ABSTRACT

Aims. I study the interaction between young AGN and their host galaxies based on their ionized gas and radio emission, and analyze possible implications for radio galaxy evolution.

Methods. The [O III] λ 5007 Å line and 5-GHz radio properties are compared and studied for a large, representative sample of GPS and CSS (i.e., young) quasars and radio galaxies, and large-scale sources using [O III] λ 5007 Å line and 5-GHz radio data from the literature and our own observations.

Results. Several correlations between the [O III] λ 5007 Å line and 5-GHz radio emission were found. The main result is that the [O III] λ 5007 Å emission is strongly correlated with the GPS/CSS source size, which indicates that the [O III] λ 5007 Å emission is enhanced significantly by the jet expansion through the host galaxy ISM. Shocks are the most likely enhancement mechanism, although jet-induced star formation could be also, partly, responsible for the [O III] λ 5007 Å emission. The data also suggests that the jet possibly decelerates as it grows, although the correlation expansion speed versus radio size is weak.

Key words. galaxies: active – galaxies: jets – galaxies: interactions – ISM: jets and outflows

1. Introduction

We still know little about how radio galaxies are born and subsequently evolve but it is generally accepted that the GHz Peaked Spectrum (GPS) and Compact Steep Spectrum (CSS) radio sources are young, smaller versions of the large-scale powerful radio sources (with a few exceptions, see e.g. Stanghellini et al. 2005 and Marecki et al. 2006).

The GPS and CSS sources are powerful but compact radio sources whose spectra are in general simple and convex with peaks close to 1 GHz or 100 MHz, respectively. The GPS sources are contained within the extent of the optical narrow emission line region ($\lesssim$1 kpc), while the CSS sources are contained within the host galaxy ($\lesssim$15 kpc, see O'Dea 1998, for a review).

Current models for the evolution of powerful radio galaxies suggest that these sources propagate from the ~10 pc to Mpc scales at roughly constant velocity through an ambient medium whose density declines as $\rho(R) \propto R^{-2}$, while the sources decline in radio luminosity as $L_{\rm rad} \propto R^{-0.5}$ (e.g. O'Dea et al. 2002, and references therein). In this scenario, GPS sources would evolve into CSS sources and these into supergalactic-size sources[1]. Such a scenario is consistent with the observed number densities of powerful radio sources as a function of linear size (e.g. O'Dea & Baum 1997; Fanti et al. 2001). However, to match observations, the radio jets of the young sources must slow down as they cross the host galaxy ISM and dim faster than predicted. The most likely mechanism to produce these effects is interaction of the radio source with the host environment (see e.g. De Young 1993; Carvalho 1994, 1998).

The characteristics (size, radio power, and young age) of GPS and CSS sources make them excellent probes of interaction (and evolution). Furthermore, they have not completely broken through the ISM, so these interactions are expected to be more important than in the larger sources. Observations of UV, H I and, especially, of the ionized gas in GPS and CSS sources suggest the presence of such interactions (e.g. Labiano et al. 2008; Holt et al. 2006; Labiano et al. 2005; Axon et al. 2000; de Vries et al. 1999, 1997).

Although evidence of interactions was found, previous investigations dealt with small samples or even just a few sources and, there has been no study of interactions for a large, representative sample of GPS and CSS sources. The small size of previous samples did not, in particular, allow the more general consequences of these interactions to be studied.

To examine the interaction between gas clouds and the radio source in a statistically significant manner, I collected a sample of almost one hundred sources, including GPS and CSS galaxies and quasars, as well as large-scale sources. I studied the properties of the [O III] λ 5007 Å line and 5-GHz radio emission trying to find traces of interaction and the responsible mechanisms.

All results have been obtained using the following cosmology $H_0 = 71$, $\Omega_{\rm M} = 0.27$, $\Omega_\Lambda = 0.73$, (Spergel et al. 2003).

2. The sample

I compiled a representative sample of GPS and CSS as well as supergalactic-sized sources for which [O III] λ 5007 Å line and 5-GHz observations were available. The sample consists

[1] Recently, the High Frequency Peakers have been added to the sequence, as possible progenitors of GPS sources (e.g. Orienti et al. 2007, and references therein).

Table 1. [O III] λ 5007 Å measurements from Kitt Peak observations.

Source	Center	$F_{[\mathrm{O\,III}]}$	*FWHM*
	Å	10^{-14} erg s^{-1} cm^{-2}	km s^{-1}
0554–026	6056.7 ± 0.7	1.49 ± 0.13	592 ± 66
0941–080	6021.9 ± 0.5	1.09 ± 0.11	370 ± 33
1345+125	5484.4 ± 0.6	4.51 ± 0.52	1187 ± 73

of literature data (O'Dea 1998; Gelderman & Whittle 1994; de Vries et al. 2000), the 2-Jy radio sources (Morganti et al. 1997; di Serego-Alighieri et al. 1994; Morganti et al. 1993; Tadhunter et al. 1993), STIS data (O'Dea et al. 2002; Labiano et al. 2005), and new Kitt Peak observations of three GPS radio galaxies: 0554–026, 0941–080, 1345+125 (Table 1).

The Kitt Peak data consists of moderate dispersion (~200 km s^{-1}) spectroscopy of the [O III] λ 5007 Å line obtained with the GoldCam CCD spectrograph at the Kitt Peak National Observatory 2.1-m telescope. I used a 600 line/mm grating with a 1.5″ slit, covering the range between 5100 and 8100 Å. The spectra were extracted and calibrated using standard IRAF procedures. After dark, bias, and flat-field correction, the images were background-subtracted to remove sky lines. Wavelength calibration was completed using HeNeAr arcs data acquired after each science exposure. The flux calibration and removal of atmospheric features were carried out using spectrophotometric standards from Massey et al. (1988).

The total number of sources included in the sample is 95 (21 GPS including our new observations, 22 CSS, and 52 large-scale sources).

3. Results and discussion

For the objects in the sample, the following properties of the [O III] λ 5007 Å line and 5-GHz radio emission were compared: *FWHM*, luminosity, asymmetry, kurtosis ([O III] λ 5007 Å line), as well as power, size and turnover frequency (radio emission).

The [O III] λ 5007 Å *FWHM* shows no correlation with radio power, turnover frequency, and [O III] λ 5007 Å luminosity. Therefore, the shock velocity (closely related to the *FWHM*, see e.g. Bicknell et al. 1997) is independent of the radio source strength, and does not affect either the luminosity of the ionized gas or the radio spectral properties of the source. However, a correlation between [O III] λ 5007 Å *FWHM* and radio source size (Fig. 1) could be present, suggesting a possible deceleration of the jet as it crosses the host galaxy:

$$\log FWHM \simeq 2.89(\pm 0.04) - 0.08(\pm 0.05) \times \log LS.$$

This correlation is not strong but could be real given that the deceleration of the jet is required to explain observations (e.g. O'Dea 1998) and the latest models predict deceleration in the jet (see e.g. Kawakatu et al. 2008). Unfortunately, there is not much [O III] λ 5007 Å *FWHM* data available to confirm any of these models.

As expected (see e.g. O'Dea & Baum 1997, Fig. 2), the sample also shows no correlation between radio power and radio size, showing that GPS, CSS, and FR2[2] sources are equally powerful ($\log P_{5-\mathrm{GHz}} \sim 10^{26-27}$ W/Hz), while FR1 sources tend to be fainter (see e.g. Baum et al. 1995; Zirbel & Baum 1995). However, for giant sources ($\gtrsim$1 Mpc), the radio power appears to decrease with size (e.g. Ishwara-Chandra & Saikia 1999).

[2] FRx corresponds to Fanaroff-Riley class x, (Fanaroff & Riley 1974).

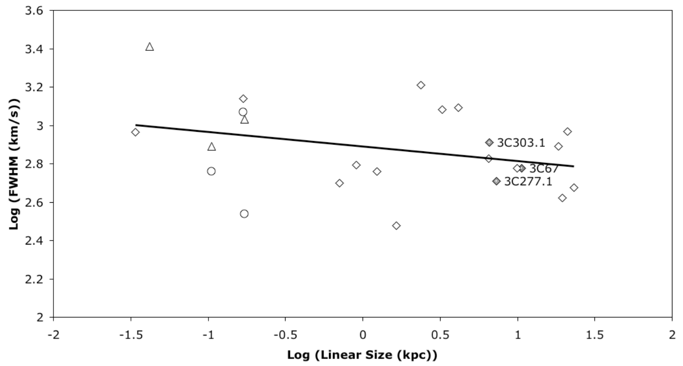

Fig. 1. Plot of the [O III] λ 5007 Å *FWHM* of the sources in Gelderman & Whittle (1994) (diamonds), de Vries et al. (2000) (triangles), our Kitt Peak (circles), and STIS (shaded diamonds) observations, and a linear fit to the data. The ionization and kinematics of 3C 67, 3C 277.1, and 3C 303.1 were studied by Labiano et al. (2005) and O'Dea et al. (2002).

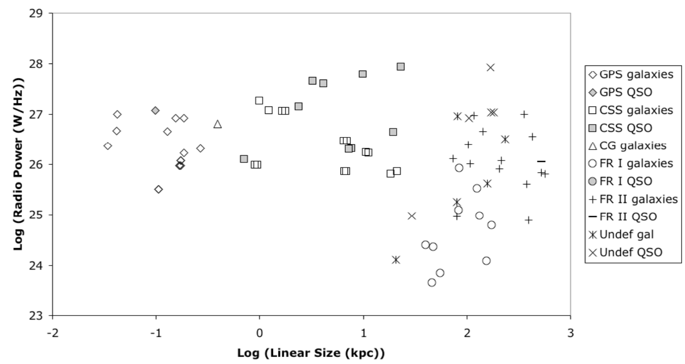

Fig. 2. Radio power at 5 GHz versus linear size for GPS, CSS and large-scale radio sources.

It is also clear that quasars appear to have stronger [O III] λ 5007 Å emission than radio galaxies, which is consistent with the unification scenario: some of the [O III] λ 5007 Å may be hidden by the torus in radio galaxies (e.g. Hes et al. 1993). The difference in [O III] λ 5007 Å emission could also be due to selection effects, since quasars are usually found at higher redshifts. On the other hand, the sample could be missing fainter quasars with luminosities similar to radio galaxies.

The sample follows the known relation (e.g. Baum & Heckman 1989; Rawlings & Saunders 1991) between [O III] λ 5007 Å luminosity and radio power (Fig. 3) for powerful ($\log P_{5-\mathrm{GHz}} \gtrsim 10^{25}$ W/Hz) radio sources. This relation is usually explained as the AGN powering both the ionized gas and radio emission. The correlations for different groups of object in our sample are:

GPS: $\log L_{[\mathrm{O\,III}]} = 32(\pm 4) + 0.4(\pm 0.1) \times \log P_{5-\mathrm{GHz}}$
CSS: $\log L_{[\mathrm{O\,III}]} = 22(\pm 4) + 0.8(\pm 0.2) \times \log P_{5-\mathrm{GHz}}$
GPS + CSS: $\log L_{[\mathrm{O\,III}]} = 25(\pm 3) + 0.7(\pm 0.1) \times \log P_{5-\mathrm{GHz}}$
GPS + CSS+FR:

$$\log L_{[\mathrm{O\,III}]} = 12(\pm 2) + 1.13(\pm 0.07) \times \log P_{5-\mathrm{GHz}}.$$

It should be noted that when combining NVSS and SDSS data (Best 2009, in prep.), this correlation is not measured for fainter ($\log P_{1.4\ \mathrm{GHz}} \lesssim 24.5$ W/Hz) radio sources, suggesting that a different mechanism may be producing the radio and [O III] λ 5007 Å emission in these sources.

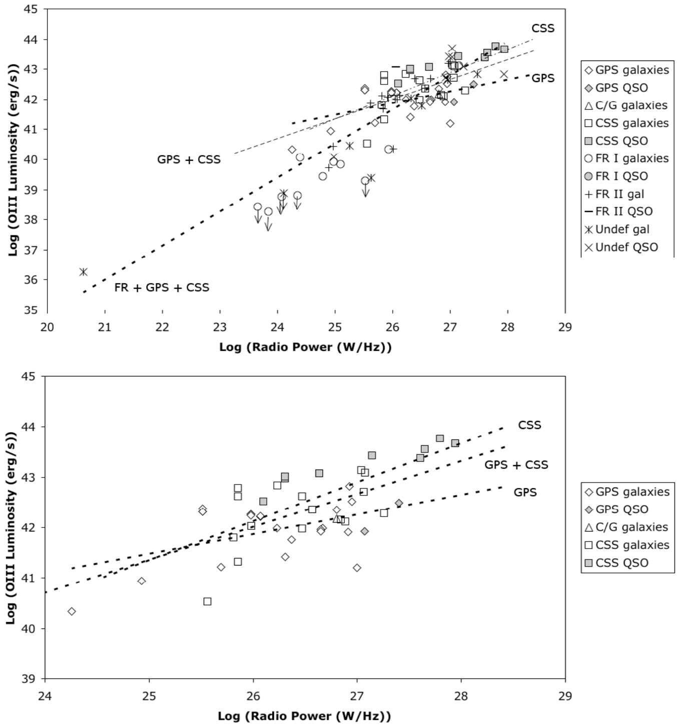

Fig. 3. Plot of the [O III] λ 5007 Å luminosity versus radio power at 5 GHz. Data for the CSS and GPS sources from Gelderman & Whittle (1994); O'Dea (1998); de Vries et al. (2000), the 2 Jy sample, and our Kitt Peak observations. Data for the large-scale radio sources from the 2 Jy sample. The IDs of the sources were updated with Zirbel & Baum (1995). I use "C/G" to label those sources with no clear ID as CSS or GPS. *Bottom panel*: as *top panel*, showing only the GPS and CSS sources.

There is no evident relation between the kurtosis or asymmetry of the [O III] λ 5007 Å line (as defined by Whittle 1985; Heckman et al. 1981) and other properties of the line. Most of the sources have a kurtosis lower than 1, suggesting the presence of broad wings in the gas. Whittle (1985) derived a similar result for his sample of Seyfert galaxies. For most sources, the asymmetry of the [O III] λ 5007 Å line profiles is almost zero, which implies that either the cocoon widens or narrows in a symmetrical way or that there are no significant variations between both sides of the source. However, ground spectra may have insufficient resolution to discern more complex structures responsible for changing shape of the line profile.

For the Gelderman & Whittle (1994) sample, O'Dea (1998) discovered that GPS galaxies tend to have lower [O III] λ 5007 Å luminosity than CSS galaxies but it was unclear if the trend would be followed by a larger sample with different selection criteria, such as quasars and large FR sources. The implications of the existence of the trend on the radio source (and host galaxy) evolution are also unclear[3]. To assess these issues, I attempted to find the trend for the sample presented here, which included not only GPS and CSS radio galaxies but also quasars and large-scale sources. I found that the GPS and CSS sources (galaxies and quasars) showed a strong correlation between [O III] λ 5007 Å luminosity and size of the radio source[4]:

GPS + CSS:

$$\log L_{[\mathrm{O\,III}]} = 42.43(\pm 0.09) + 0.46(\pm 0.09) \times \log LS_{5-\mathrm{GHz}}$$

GPS*+CSS:

$$\log L_{[\mathrm{O\,III}]} = 42.44(\pm 0.08) + 0.4(\pm 0.1) \times \log LS_{5-\mathrm{GHz}}$$

where GPS* means the complete sample of GPS, excluding its smallest source (1718–649), to test if it the source data dominates the correlation.

In principle, this correlation could be due to the AGN enhancing both the radio and emission gas luminosities through photons. However, for the same radio power, small sources (GPS) are systematically fainter in [O III] λ 5007 Å than larger (CSS) sources.

I propose a scenario where the expansion of the radio source through the host ISM is triggering and/or enhancing the [O III] λ 5007 Å emission by direct interaction. Some contribution from the AGN light must be present but AGN light alone could not produce a correlation with size. Furthermore, the fact that the correlation disappears for larger radio sources ($\gtrsim$15−20 kpc) supports this model: when the radio lobes leave the host galaxy, the [O III] λ 5007 Å luminosity drops (Fig. 4).

This scenario is also supported by previous observations providing evidence of strong interaction between the jet and surrounding ISM, as well as proof of shock-ionized [O III] λ 5007 Å emission (e.g. Labiano et al. 2005; O'Dea et al. 2003). Jet-ISM interactions are also found through H I studies (e.g. Labiano et al. 2006; Holt et al. 2006, and references therein) and predicted by jet expansion models (e.g. Jeyakumar et al. 2005; Saxton et al. 2005).

Another interesting enhancing mechanism to consider is that the jet could, at least partly, boost [O III] λ 5007 Å emission by indirect mechanisms such as jet-induced star formation (Labiano et al. 2008, in prep.), but new data are required to assess the possible contribution of recently formed stars. The hosts of GPS and CSS sources are usually elliptical galaxies so it is unlikely that the average/normal stellar population of the host galaxy has a strong contribution to the [O III] λ 5007 Å emission. These "normal" stars would not, however, create a correlation with radio jet size (and jet-induced stars would).

The correlations are as follows:

GPS: $\log L_{[\mathrm{O\,III}]} = 42.8(\pm 0.2) + 0.8(\pm 0.2) \times \log LS_{5-\mathrm{GHz}}$
GPS*: $\log L_{[\mathrm{O\,III}]} = 42.5(\pm 0.4) + 0.5(\pm 0.4) \times \log LS_{5-\mathrm{GHz}}$
CSS: $\log L_{[\mathrm{O\,III}]} = 42.6(\pm 0.2) + 0.2(\pm 0.3) \times \log LS_{5-\mathrm{GHz}}$.

The correlation tends to disappear when the sample is divided into different types of sources. This could be due to low statistics or the smaller range of sizes covered by each type. GPS sources could show lower [O III] λ 5007 Å emission due to high obscuration. However, it is more likely that young compact sources are too small to strongly affect their environment. This effect has also been observed in star formation histories of GPS hosts (Labiano et al. 2008). The UV luminosities of GPS sources appear to be as high as those of CSS sources. Furthermore, the UV luminosity of GPS sources could be correlated with their

[3] A direct consequence is that it is more difficult to find optical counterparts of GPS sources than CSS sources.

[4] Note that the trend is also suggested by Fig. 3 and the different correlations between radio power and [O III] λ 5007 Å luminosity for GPS and CSS sources.

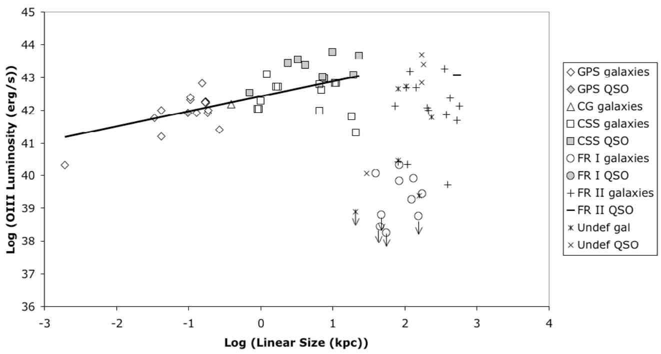

Fig. 4. Plot of the [O III] luminosity versus linear size of the radio source, showing the correlation for GPS and CSS sources. Data from the same references as Fig. 3.

radio power (Labiano et al. 2008). These two effects suggest that obscuration is not significantly strong for GPS sources or, at least, similar to that in CSS.

Concerning the overall scenario of radio source evolution, where GPS and CSS sources evolve into the larger FR sources, the visual inspection of Fig. 4 suggests that CSS sources would evolve into FR2. Some authors also found a possible decreasing trend linking FR2 to FR1 (Best 2008, private communication) with increasing size. However, our sample may have insufficient number of supergalactic-sized sources to address evolution thoroughly beyond ~15–20 kpc, and a study of the FR2 – FR1 connection is therefore beyond the scope of this letter. Extensive discussions about the FR2 – FR1 connection can be found in the literature: e.g. Müller et al. (2004); Best et al. (2005); Wold et al. (2007) and references therein, or classical papers such as Baum et al. (1995); Zirbel & Baum (1995).

4. Summary of main results and future work

The aim of this project was to improve our understanding of radio jet-host interaction in young AGN by studying the [O III] λ 5007 Å line and 5-GHz radio emission properties of GPS and CSS sources. I compiled a large, representative sample of GPS and CSS quasars, combined with FR 1 and FR 2 sources (to help establish an evolution timeline) from published data, and our observations.

The main result of the study is that the [O III] λ 5007 Å emission is clearly enhanced by the jet expansion through the host galaxy ISM. This is consistent with previous observations as well as numerical models of jet expansion. However, further work is required (Labiano et al. 2008, in prep.):

- the supergalactic-size sample needs to be increased, to establish evolution when the radio lobes leave the host galaxy;
- evaluate the strength of the jet shocks and study their capability to form stars (which could enhance the [O III] λ 5007 Å) as well as direct contribution of the shocks to the [O III] λ 5007 Å emission;
- study of star formation and AGN tracers (such as X-rays, 24 and 70 μm dust, line ratios, PAH) to identify and evaluate different mechanisms and contributions to the [O III] λ 5007 Å emission;
- apply and improve jet expansion models to reproduce the results.

A parallel result to the [O III] λ 5007 Å emission – radio source size correlation is that it will be more difficult to find optical counterparts of GPS than CSS sources.

The data suggest a possible deceleration of the jet as it crosses the host galaxy ISM, which is required by most radio source evolution models. However, the correlation is too weak and a much larger sample, with higher resolution spectra, is needed. The sample also reflects some already known results such as quasars showing lower [O III] λ 5007 Å luminosity than radio galaxies, radio power being correlated with [O III] λ 5007 Å luminosity, and radio power being independent of the radio source size.

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