Circumnuclear Gaseous Kinematics and Excitation of Four Local Radio Galaxies

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Jekyll Island, June 29, 2017
Radio galaxies

- Radio jets interact with gas, generating shock ionization and outflows.

- Energy injection into the ISM (Fabian 2012).

- AGN feedback may quench star formation if powerful enough ($\dot{E} > 5\%L_{\text{bol}}$, Di Matteo et al. 2005)
Our sample

GMOS-IFU data from Gemini Telescopes (3.5′′ × 5′′ FoV, ~ 0.6′′ spatial resolution, $R \sim 3600$), in order to:

- Map circumnuclear gas kinematics and excitation.
- Study possible jet-gas interaction.
- Quantify feedback impact in the host galaxies.

Observed galaxies ($z < 0.07$): Arp 102B, Pictor A, 3C 33 e 4C +29.30
Arp 102B

- Elliptical galaxy (E0), $d = 104.9$ Mpc ($z = 0.02$, $\approx 490$ pc/″).
- Interaction with Arp 102A.
- Fathi et al. 2011: nuclear spiral arms correlated with jet.
Arp 102B - Channel maps

- Gas rotating disk.
- Radio jet along redshifted and blueshifted gas emission.
- Outflowing gas close to the plane of sky.

Couto et al. 2013

Couto et al. 2013
Arp 102B - Gas excitation


![Graphs showing line ratios of [OIII]/Hβ, [NII]/Hα, [OII]/Hα, and [SII]/Hα](#) for different velocities.]

Couto et al. 2013
Pictor A

- $d = 153$ Mpc ($z = 0.03$, 690 pc/′
- Extended double-lobed jet (> 200 kpc).
- Tidal tail: $\sim 10^7$ yrs interaction.
Pictor A - Flux distributions

- Non-resolved broad component ($\sigma > 300 \text{ km s}^{-1}$).
- Narrow component emission extended along a bar-like structure.

Couto et al. 2016
Pictor A - Gas excitation

- $[\text{O} \, \text{III}] / \text{H} \beta$ from Fillipenko (1985, triangles) and Simkin et al. (1999, diamonds).
- Low $[\text{N} \, \text{II}] / \text{H} \alpha$.
- Low metallicities for AGN ($12 + \log(O/H) \sim 8.39$): accretion of gas from interaction.

![Graph showing gas kinematics and excitation of low-z radio galaxies](image-url)
3C 33

- Seyfert 2, $d \approx 266$ Mpc ($z = 0.06, 1.15$ kpc/″).
- Extended emission in spiral arms ($\approx 4$ kpc).
- Radio jet with extension of $\sim 120$ kpc.

VLA image (Leahy & Perley 1991) and ACS-HST image (Tremblay et al. 2009)
Rotation pattern with distortions in the nucleus.

$\sigma \sim 170 \text{ km s}^{-1}$ almost perpendicular to the radio jet.

Couto et al. 2017
3C 33 - Outflowing gas

- Increase of \([\text{N}\ II]/\text{H}\alpha\) along residuals: laterally expanding gas.

Rotation model

\([\text{N}\ II]/\text{H}\alpha\) channel maps
3C 33 - Outflowing gas

- High residuals, $\sigma$ and temperature.
- Rotation and outflowing velocity regimes.

Couto et al. 2017
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4C +29.30

- Elliptical galaxy, $d \approx 289$ Mpc ($z = 0.06$, 1.24 kpc/"").

- Feedback and interaction signatures in X-rays (Siemiginowska et al. 2012).

4C +29.30 composite image: optical (green), radio (pink) and X-rays (blue, $\approx 50'' \times 50''$, Siemiginowska et al. 2012).
4C +29.30 - $F$, $\nu$ and $\sigma$ distributions

- Extended emission $\sim 6$ kpc along spiral arms-like structure.
- “Southern knot”: blueshifted region $\approx 1''$ from the nucleus, $\sigma \sim 250$ km s$^{-1}$.

Couto et al. (in prep)

Gas kinematics and excitation of low-z radio galaxies

Jekyll Island, June 29, 2017
4C +29.30 - Channel maps

- Southern knot with $v > 600\ \text{km s}^{-1}$: signature of outflow.
- Extended emission may be related to the radio jet.

Couto et al. (in prep)
Summary

- Higher [N II]/Hα, [S II]/Hα and [O I]/Hα are usually observed in regions related to outflows, tracing shocks.
- $\sigma \geq 200 \text{ km s}^{-1}$ usually perpendicular to the radio jet axis, thus outflows seems to be in lateral expansions.
- Presence of feeding mechanisms such as spiral arms and bars.
- High ionized gas masses ($\sim 10^8 M_\odot$) indicate accretion of gas in this sample, which presents interaction with companions.
- Circumnuclear outflowing gas with low kinetic power ($\dot{E} \sim 0.05\% L_{bol}$), but may be enough to inhibit star formation ($\Sigma_{SFR} \sim 10^{-3} M_\odot \text{ ano}^{-1} \text{kpc}^{-2}$ using Kennicutt 1998).
- Kinetic power may be up to two magnitudes higher when looking into molecular gas (eg. 3C 293, Mahony et al. 2016).

More info: Couto et al. 2013, 2016, 2017
Integral Field Unit (IFU) of GMOS, telescope Gemini spectrograph.

One-slit mode: $3.5'' \times 5''$.

Higher spectral coverage ($R \sim 3600$).

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Program ID</th>
<th>$t_{\text{exp}}(s)$</th>
<th>Grating</th>
<th>$\Delta \lambda$ (Å)</th>
<th>Seeing (&quot;&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arp 102B</td>
<td>GN-2007A-Q-57</td>
<td>$6 \times 900$</td>
<td>B600+G5303</td>
<td>4400-7300</td>
<td>0.6&quot;</td>
</tr>
<tr>
<td>Pictor A</td>
<td>GS-2004B-Q-25</td>
<td>$9 \times 600$</td>
<td>R400+G5325</td>
<td>5600-9925</td>
<td>0.57&quot; × 0.82&quot; (elíptico)</td>
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<tr>
<td>3C 33</td>
<td>GN-2010B-Q-66</td>
<td>$8 \times 940$</td>
<td>B600+G5307</td>
<td>4400-7300</td>
<td>0.5&quot;</td>
</tr>
<tr>
<td>4C +29.30</td>
<td>GN-2016A-Q-77</td>
<td>$15 \times 1140$</td>
<td>B600+G5307</td>
<td>4400-7300</td>
<td>0.7&quot;</td>
</tr>
</tbody>
</table>
Emission line measurements

- Fitting of Gaussians or Gauss-Hermite polynomials.
- Integrated flux, centroid velocity and velocity dispersions ($h3$ and $h4$ moments for GH).
- Noise uncertainties: 100 fittings in each pixel, adding random noise.

**Figura:** Pictor A

**Figura:** 3C 33 ([O III])

$h3 = 0.08$

$h4 = 0.09$
Channel maps

- Spectral bands extracted along the emission line profile.
- Allows the investigation of the emitting gas in different velocity bins.
Gas excitation mechanisms

- MAPPINGS III models (Allen+ 08, Groves+ 04a,b)
- Photoionization: ionizing continuum in the central source with $F_\nu \propto \nu^\alpha$.
- Shocks: gas ionization with shock velocities of $100 < v_s < 1100 \text{ km s}^{-1}$.

Diagnostic diagrams (Kewley+ 06).
Physical features of the gas

- Reddening assuming recombination case B (Osterbrock & Ferland 06) and Cardelli et al. 1989 law:

\[
E(B - V) = 2.22 \log \frac{F(H\alpha)/F(H\beta)}{3.1}
\] (1)


- Emitting gas mass:

\[
M \approx 7 \times 10^5 \frac{L_{41}(H\beta)}{n_e^2} M_\odot
\] (2)

- Outflow mass rate:

\[
\dot{M}_{out} = m_p n_e v_{out} A f
\] (3)

- Accretion mass rate:

\[
\dot{m} = \frac{L_{bol}}{c^2 \eta} \approx 1.8 \times 10^{-3} \left( \frac{L_{44}}{\eta} \right) M_\odot \text{ yr}^{-1}
\] (4)
Rotating model

Assuming the gas is rotating in a disk with keplerian movement, the observed radial velocity is given by (Bertola+ 91):

\[ v(R, \Psi) = v_{sys} + \frac{A R \cos(\Psi - \Psi_0) \sin \theta \cos^p \theta}{\{ R^2[\sin^2(\Psi - \Psi_0) + \cos^2 \theta \cos^2(\Psi - \Psi_0)] + c_0^2 \cos^2 \theta \}^{p/2}} \]

- **R e \Psi**: coordinates in the plane of the sky.
- **\Psi_0**: angle of the line of the nodes.
- **\theta**: disk inclination with the plane of the sky.
- **\nu_{sys}**: systemic velocity.
- **A**: rotation amplitude.
- **c_0 e p**: concentration parameter and curve steepness.

Residuals between the observation and model: non-rotating components.
Arp 102B - Flux distribution

continuum$\lambda 5673$

$[\text{OIII}]\lambda 5007$

H$\alpha \lambda 6563$
Arp 102B - Centroid velocity and $\sigma$
Arp 102B - Gas excitation

- BPT diagram: values between Seyfert and LINER.

Couto et al. 2013
**Arp 102B - Gas excitation**

- Shocks: $400 < v_{\text{shock}} < 500 \text{ km s}^{-1}$ and $10^{-4} < B < 2.0 \mu\text{G}$.
- Photoionization with $n_H = 1000 \text{ cm}^{-3}$: $-1.7 < \alpha < -1.4$ and $-3.0 < \log U < -2.5$. 

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![Graphs of line ratios for different shock velocities](image-url)
Pictor A - Line fitting

- 2 components: narrow ($< 300 \text{ km s}^{-1}$) and broad ($> 300 \text{ km s}^{-1}$).
Disturbed kinematics dominated by non-rotating components.

Low $\sigma$ along bar-like structure ($\sim 50\,\text{km}\,\text{s}^{-1}$).
- PC4: blueshifts along the far side of the jet.
- Possible bipolar outflow in lateral expansions (cannot rule out rotation).
3C 33 - Line fitting

- Initially fitted Gauss-Hermite.
- $|h3| > 0.03$: two Gaussians.
- $|h3| < 0.03$: one Gaussian.
3C 33 - 2-Gaussians $F$, $\nu$, $e$, $\sigma$ distribution

- Broad component ($\sigma > 130 \text{ km s}^{-1}$): “nuclear strip”.
- Narrow component ($\sigma < 130 \text{ km s}^{-1}$): traces rotation and spiral arms.
3C 33 - Line ratios

- $\text{[N II]} / \text{H}\alpha$, $\text{[S II]} / \text{H}\alpha$ e $\text{[O I]} / \text{H}\alpha$: shocks in the nuclear strip.
- $\text{[O I]} / \text{H}\alpha$: shocks along the spiral arms.
3C 33 - Line ratios

- [O III]/Hβ: ionization along the radio jet.
- [S II]6717/31: \( n_e \sim 300 \text{ cm}^{-3} \) in the nuclear strip.
- Hα/Hβ: dust lanes \((A_v \sim 1.5 \text{ mag})\).
4C +29.30 - Line ratios

- $[\text{N}\ II]/\text{H}{\alpha}$ and $[\text{S}\ II]/\text{H}{\alpha}$: high and low values in redshifts and blueshifts, respectively.
- $[\text{O}\ III]/\text{H}\beta$: values decrease with the distance to the nucleus.
4C +29.30 - Electron density

- $n_e > 300 \text{ cm}^{-3}$ between the nucleus and southern knot.
- Apparent correlation with the radio jet.