Circumnuclear Gaseous Kinematics and Excitation of Four Local Radio Galaxies

Guilherme S. Couto

T. Storchi-Bergmann, A. Robinson, R.A. Riffel, P. Kharb
D. Lena, A. Schnorr-Müller

UFSC, Florianópolis, Brazil

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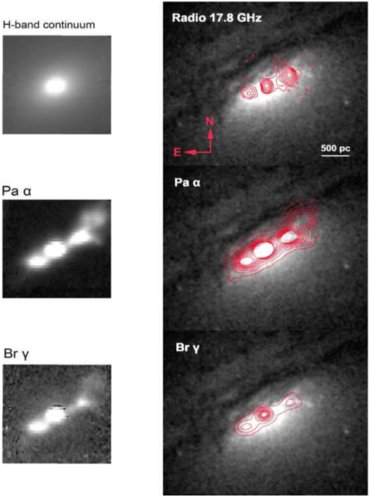
UNIVERSIDADE FEDERAL
DE SANTA CATARINA

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 ($\dot{E} > 5\% L_{\rm bol}$, Di Matteo et al. 2005)



IC5063, Dasyra et al. 2015

Our sample

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

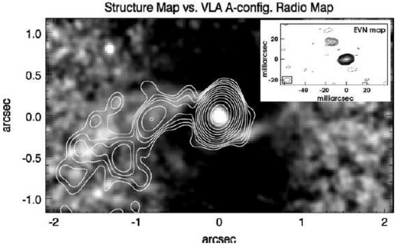
- Map circumnuclear gas kinematics and excitation.
- Study possible jet-gas interaction.
- Quantify feedback impact in the host galaxies.

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

Arp 102B

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

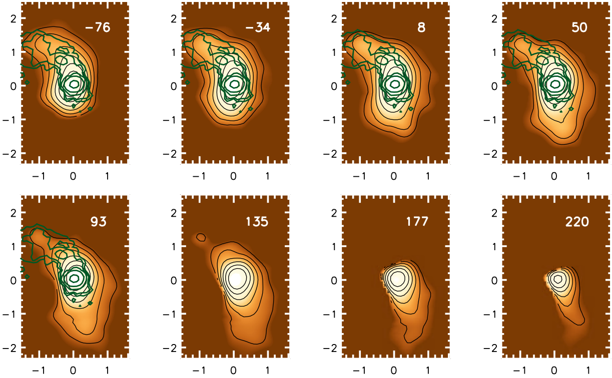
Arp 102A and Arp 102B pair (Rick Johnson).



Fathi et al. 2011

Arp 102B - Channel maps

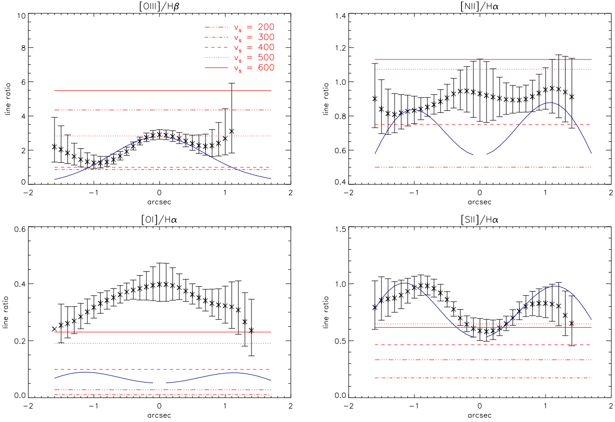
- Gas rotating disk.
- Radio jet along redshifted and blueshifted gas emission.
- Outflowing gas close to the plane of sky.



Couto et al. 2013

Arp 102B - Gas excitation

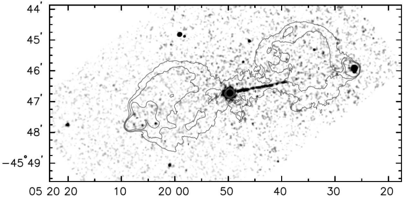
- Comparison with MAPPINGS III models (Groves et al. 2004, Allen et al. 2008): photoionization and shocks.



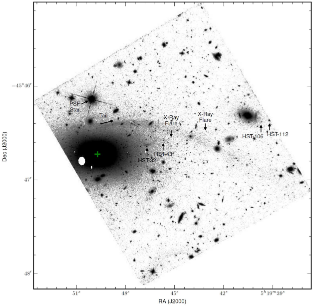
Couto et al. 2013

Pictor A

- $d = 153\,\mathrm{Mpc}$ ($z = 0.03$, 690 pc/$''$).
- Extended double-lobed jet (> 200 kpc).
- Tidal tail: $\sim 10^7$ yrs interaction.



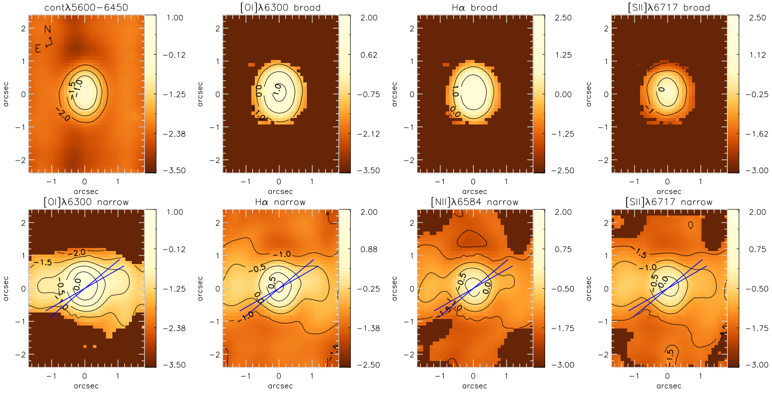
VLA contours and X-ray image (Wilson et al. 2001)



WFC3/IR-HST image (Gentry et al. 2015)

Pictor A - Flux distributions

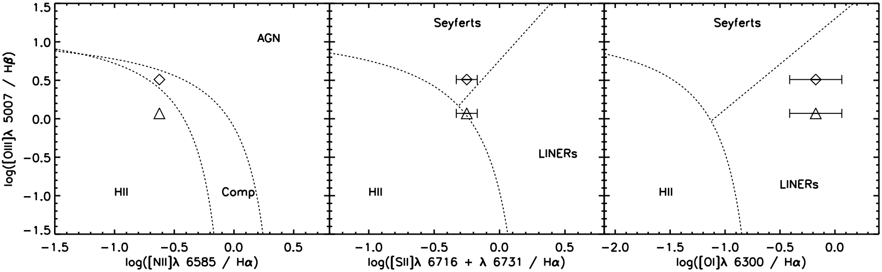
- Non-resolved broad component ($\sigma > 300\,\mathrm{km\,s^{-1}}$).
- Narrow component emission extended along a bar-like structure.



Couto et al. 2016

Pictor A - Gas excitation

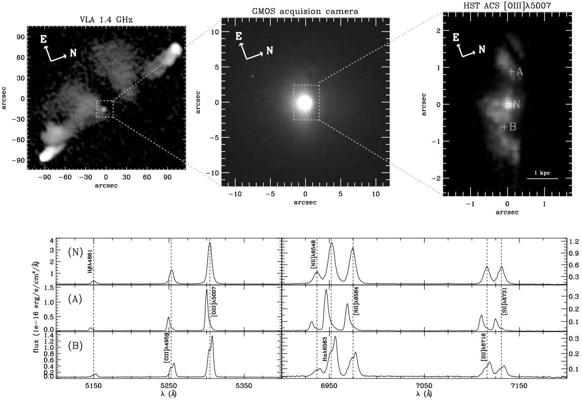
- [O III]/Hβ from Fillipenko (1985, triangles) and Simkin et al. (1999, diamonds).
- Low [N II]/Hα.
- Low metallicities for AGN ($12 + log(O/H) \sim 8.39$): accretion of gas from interaction.



Couto et al. 2016

3C 33

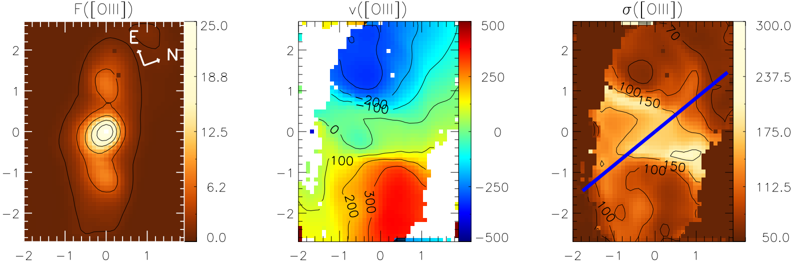
- Seyfert 2, $d \approx 266\,\text{Mpc}$ ($z = 0.06$, 1.15 kpc/$''$).
- Extended emission in spiral arms ($\approx 4\,\text{kpc}$).
- Radio jet with extension of $\sim 120\,\text{kpc}$.



VLA image (Leahy & Perley 1991) and ACS-HST image (Tremblay et al. 2009)

3C 33 - F, v and σ distributions

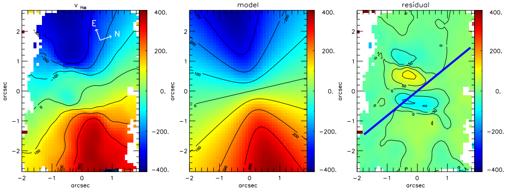
- Rotation pattern with distortions in the nucleus.
- $\sigma \sim 170\,\mathrm{km\,s^{-1}}$ almost perpendicular to the radio jet.



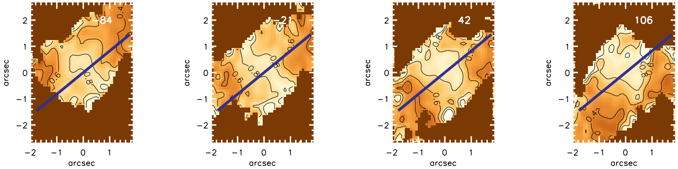
Couto et al. 2017

3C 33 - Outflowing gas

- Increase of [N II]/Hα along residuals: laterally expanding gas.



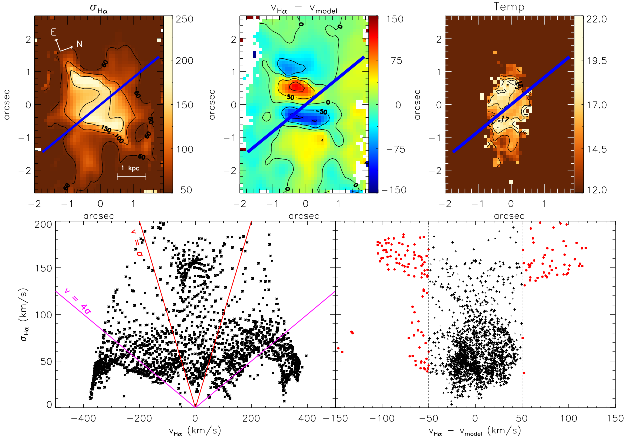
Rotation model



[N II]/Hα channel maps

3C 33 - Outflowing gas

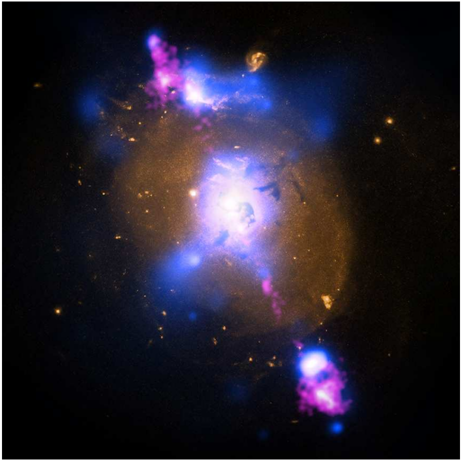
- High residuals, σ and temperature.
- Rotation and outflowing velocity regimes.



Couto et al. 2017

4C +29.30

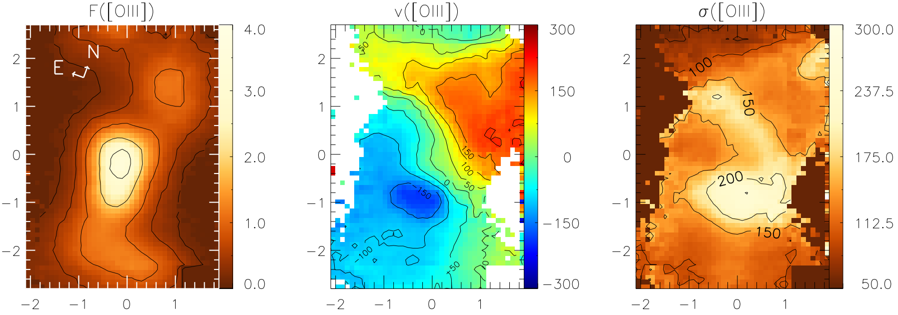
- Elliptical galaxy, $d \approx 289\,\mathrm{Mpc}$ ($z = 0.06$, 1.24 kpc/$''$).
- Feedback and interaction signatures in X-rays (Siemiginowska et al. 2012).



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, v and σ distributions

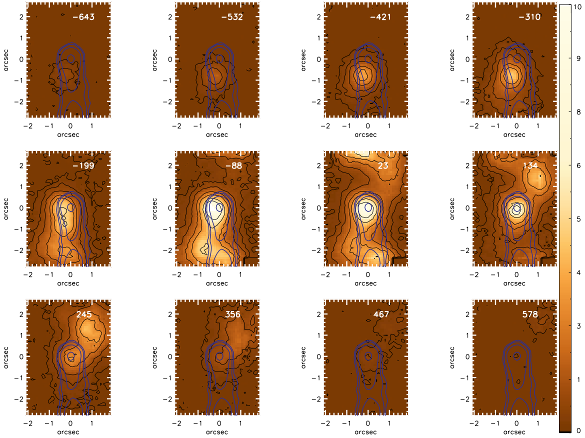
- Extended emission $\sim 6\,\mathrm{kpc}$ along spiral arms-like structure..
- "Southern knot": blueshifted region $\approx 1''$ from the nucleus, $\sigma \sim 250\,\mathrm{km\,s^{-1}}$.



Couto et al. (in prep)

4C +29.30 - Channel maps

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



Couto et al. (in prep)

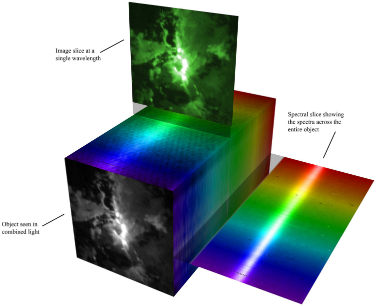
Summary

- Higher [N II]/Hα, [S II]/Hα and [O I]/Hα are usually observed in regions related to outflows, tracing shocks.
- $\sigma \geq 200\,\mathrm{km\,s^{-1}}$ 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 acretion 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 ($\Sigma_{SFR} \sim 10^{-3}\,M_\odot$ ano^{-1} 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

Observations

- Integral Field Unit (IFU) of GMOS, telescope Gemini spectrograph.
- One-slit mode: $3.5'' \times 5''$.
- Higher spectral coverage ($R \sim 3600$).



Galaxy	Program ID	$t_{exp}(s)$	Grating	$\Delta\lambda$ (Å)	*Seeing* ($''$)
Arp 102B	GN-2007A-Q-57	6×900	B600+_G5303	4400-7300	$0.6''$
Pictor A	GS-2004B-Q-25	9×600	R400+_G5325	5600-9925	$0.57'' \times 0.82''$ (elíptico)
3C 33	GN-2010B-Q-66	8×940	B600+_G5307	4400-7300	$0.5''$
4C +29.30	GN-2016A-Q-77	15×1140	B600+_G5307	4400-7300	$0.7''$

Emission line measurements

- Fitting of Gaussians or Gauss-Hermite polynomials.
- Integrated flux, centroid velocity and velocity dispersions (*h*3 and *h*4 moments for GH).
- Noise uncertainties: 100 fittings in each pixel, adding random noise.

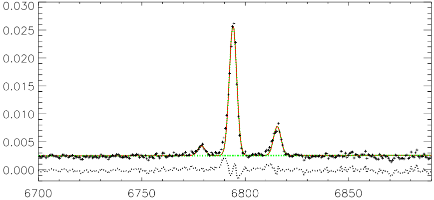


Figura: Pictor A

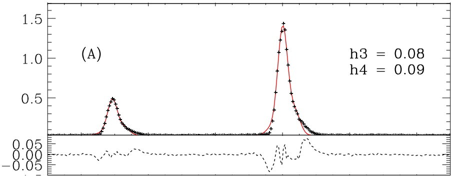
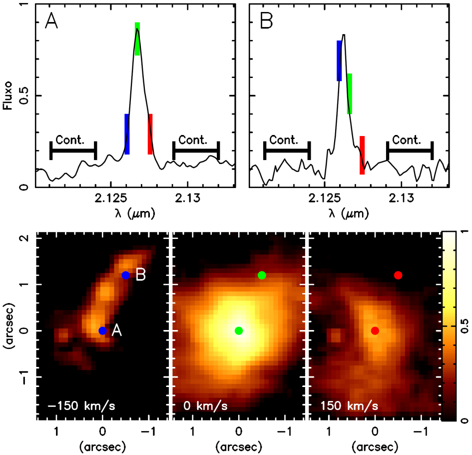


Figura: 3C 33 ([O III])

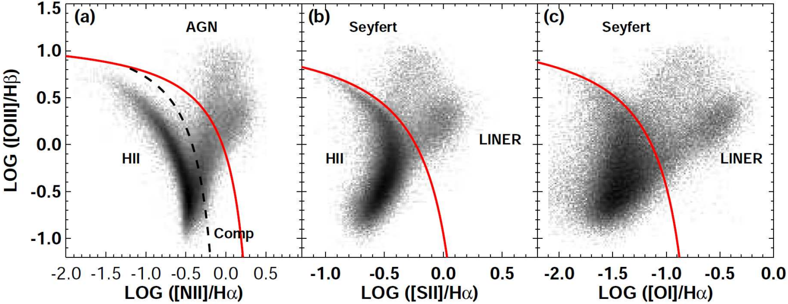
Channel maps

- 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 $100 < v_s < 1100\,\mathrm{km\,s^{-1}}$.



Diagnostic diagrams (Kewley+ 06).

Physical features of the gas

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

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

- Eletron density: [S II]λ6716/6731 using TEMDEN (De Robertis et al. 1987).
- Emitting gas mass:

$$M \approx 7 \times 10^5 \frac{L_{41}(H\beta)}{n_3^2} M_\odot \quad (2)$$

- Outflow mass rate:

$$\dot{M}_{out} = m_p \, n_e \, v_{out} \, A \, f \quad (3)$$

- Accretion mass rate:

$$\dot{m} = \frac{L_{bol}}{c^2 \eta} \approx 1.8 \times 10^{-3} \left(\frac{L_{44}}{\eta} \right) \mathrm{M_\odot \, yr^{-1}} \quad (4)$$

Rotating model

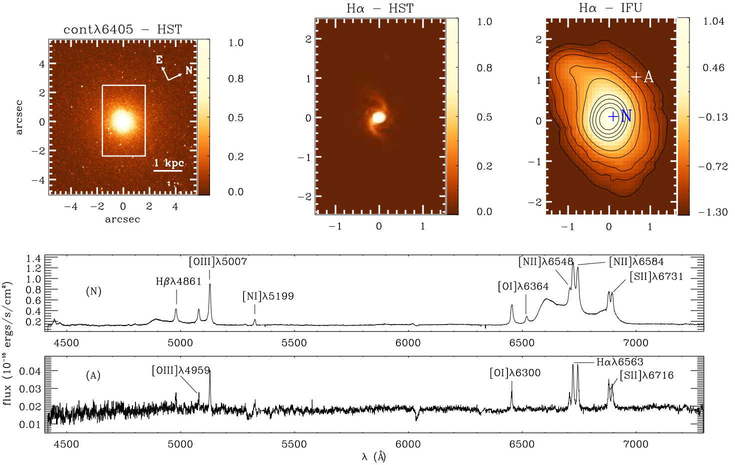
- Assuming the gas is rotating in a disk with keplerian movement, the observed radial velocity is given by (Bertola+ 91):

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

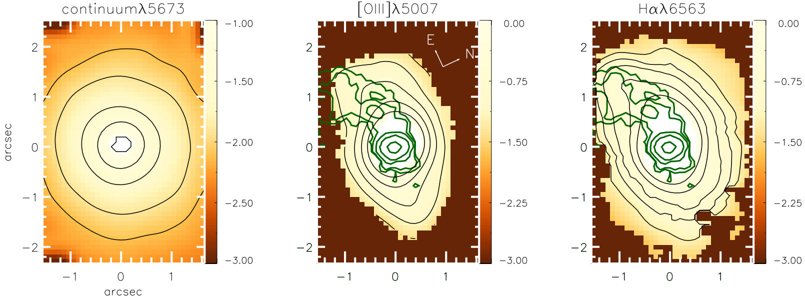
- R e Ψ: coordinates in the plane of the sky.
- Ψ_0: angle of the line of the nodes.
- θ: disk inclination with the plane of the sky.
- v_{sys}: systemic velocity.
- A: rotation amplitude.
- c_0 e p: concentration parameter and curve steepness

- Residuals between the observation and model: non-rotating components.

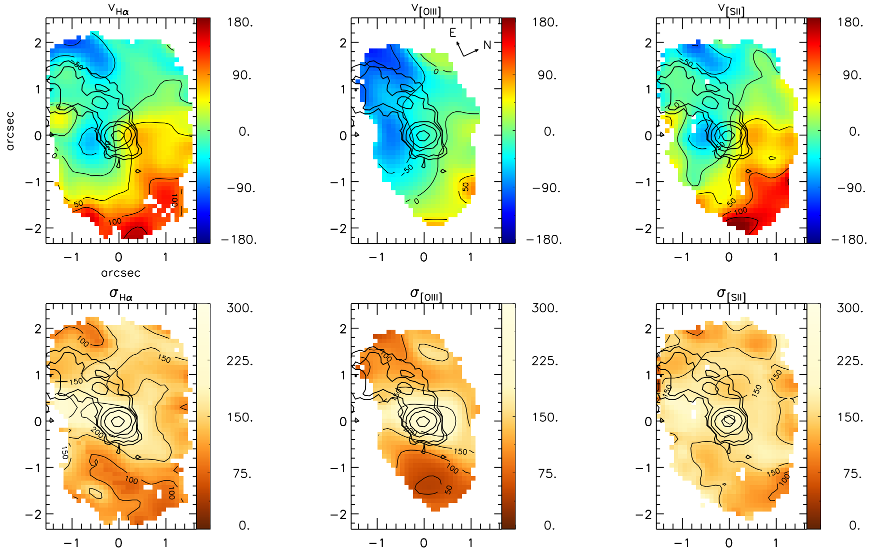
Arp 102B


contλ6405 – HST
Hα – HST
Hα – IFU
arcsec
E
N
1 kpc
+A
+N
(N)
(A)
Hβλ4861
[OIII]λ5007
[NI]λ5199
[OI]λ6364
[NII]λ6548
[NII]λ6584
[SII]λ6731
[OIII]λ4959
[OI]λ6300
Hαλ6563
[SII]λ6716
flux (10⁻¹⁵ ergs/s/cm²)
λ (Å)

Arp 102B - Flux distribution

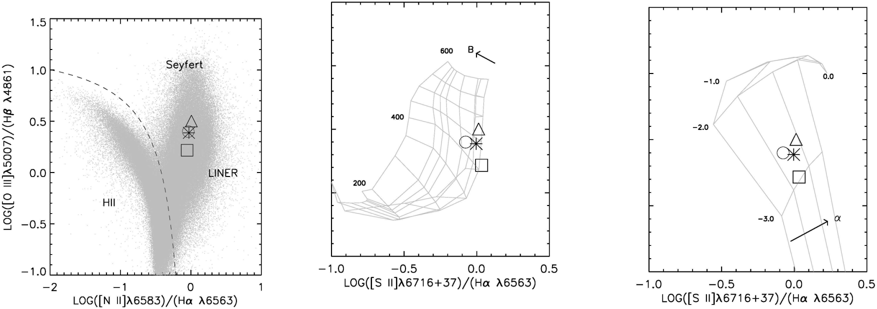


Arp 102B - Centroid velocity and σ



Arp 102B - Gas excitation

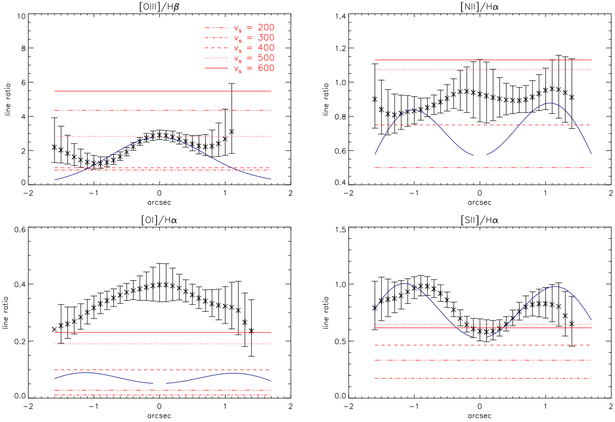
- BPT diagram: values between Seyfert and LINER.
- Comparison with MAPPINGS III models (Groves et al. 2004, Allen et al. 2008): photoionization and shocks.



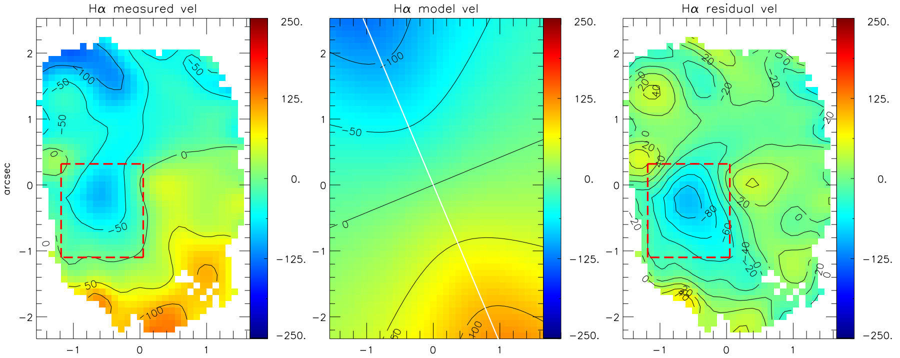
Couto et al. 2013

Arp 102B - Gas excitation

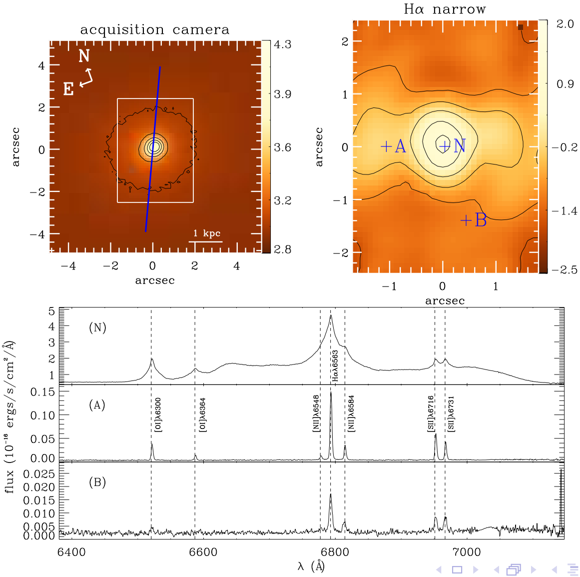
- Shocks: $400 < v_{shock} < 500\,\mathrm{km\,s^{-1}}$ and $10^{-4} < B < 2.0\,\mu$G.
- Photoionization with $n_H = 1000\,\mathrm{cm^{-3}}$: $-1.7 < \alpha < -1.4$ and $-3.0 < \log U < -2.5$.



Arp 102B - Rotation model

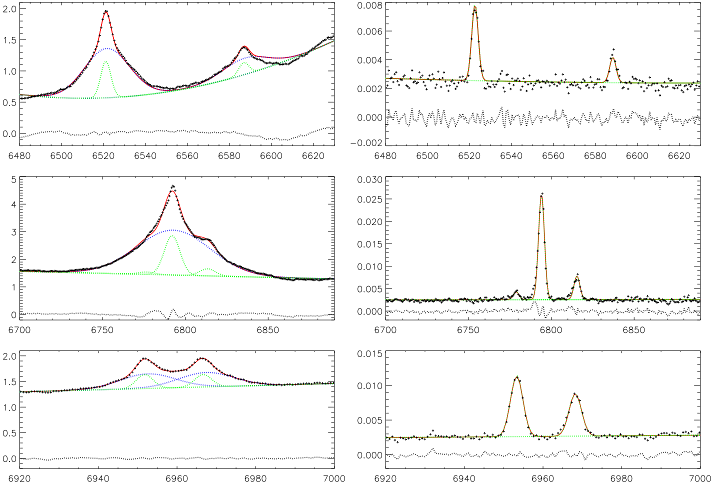


Pictor A


acquisition camera
N
E
1 kpc
arcsec
Hα narrow
+A
+N
+B
(N)
(A)
(B)
Hαλ6563
[OI]λ6300
[OI]λ6364
[NII]λ6548
[NII]λ6584
[SII]λ6716
[SII]λ6731
flux (10⁻¹⁶ ergs/s/cm²/Å)
λ (Å)

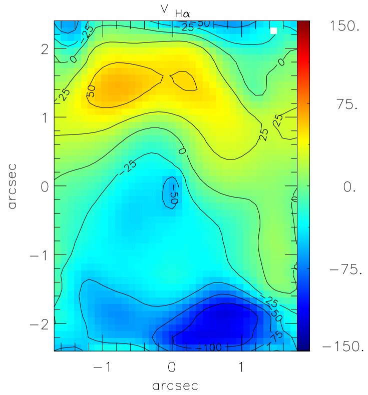
Pictor A - Line fitting

- 2 components: narrow ($< 300\,\mathrm{km\,s^{-1}}$) and broad ($> 300\,\mathrm{km\,s^{-1}}$).



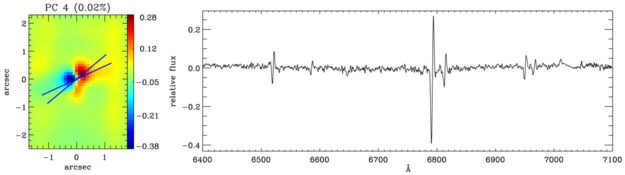
Pictor A - Centroid velocity and velocity dispersion

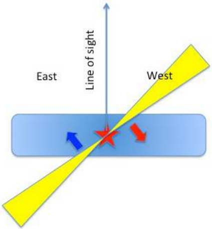
- Disturbed kinematics dominated by non-rotating components.
- Low σ along bar-like structure ($\sim 50\,\mathrm{km\,s^{-1}}$).



Pictor A - PCA Analysis

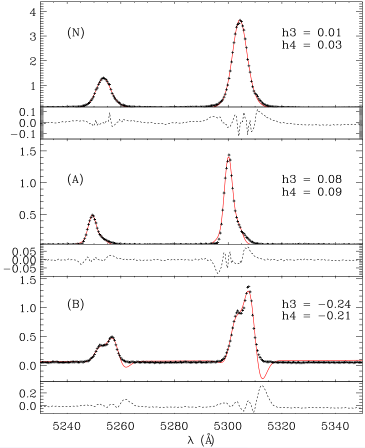
- PC4: blueshifts along the far side of the jet.
- Possible bipolar outflow in lateral expansions (cannot rule out rotation).

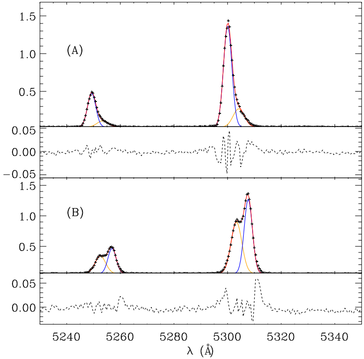




3C 33 - Line fitting

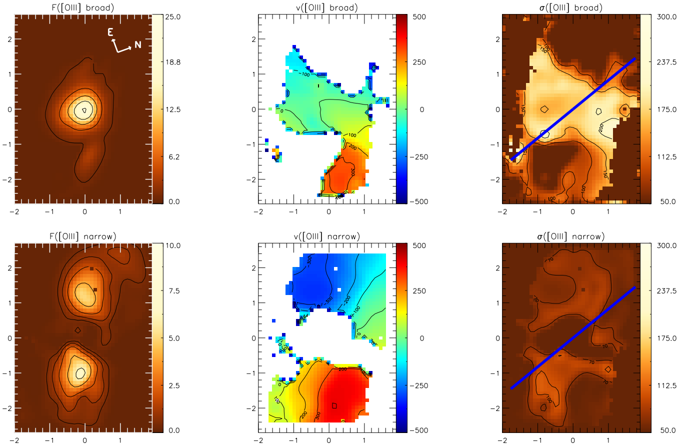
- Initially fitted Gauss-Hermite.
- $|h3|$ or $|h4| > 0.03$: two Gaussians.
- $|h3|$ or $|h4| < 0.03$: one Gaussian.





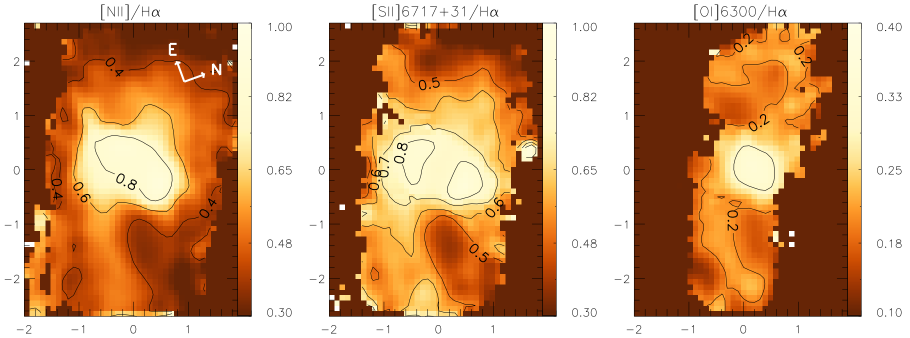
3C 33 - 2-Gaussians F, v e σ distribution

- Broad component ($\sigma > 130\,\mathrm{km\,s^{-1}}$): "nuclear strip".
- Narrow component ($\sigma < 130\,\mathrm{km\,s^{-1}}$): traces rotation and spiral arms.



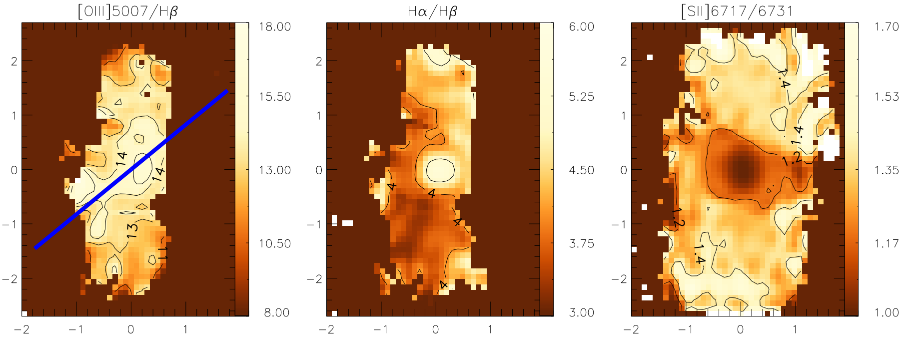
3C 33 - Line ratios

- [N II]/Hα, [S II]/Hα e [O I]/Hα: shocks in the nuclear strip.
- [O I]/Hα: shocks along the spiral arms.

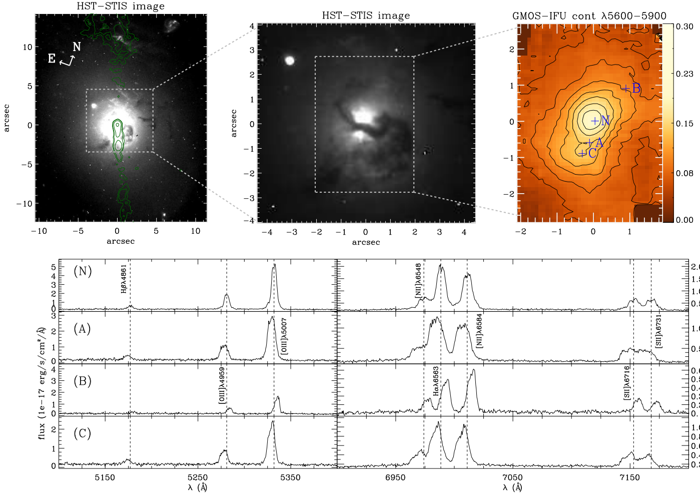


3C 33 - Line ratios

- [O III]/Hβ: ionization along the radio jet.
- [S II]6717/31: $n_e \sim 300\,\mathrm{cm}^{-3}$ in the nuclear strip.
- Hα/Hβ: dust lanes ($A_v \sim 1.5$ mag).

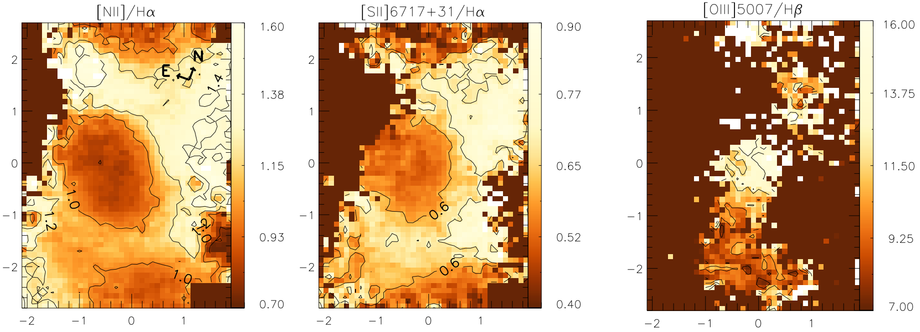


4C +29.30


HST−STIS image
HST−STIS image
GMOS−IFU cont λ5600−5900
E
N
arcsec
+B
+N
+A
+C
(N)
(A)
(B)
(C)
Hβλ4861
[OIII]λ4959
[OIII]λ5007
[NII]λ6548
Hαλ6563
[NII]λ6584
[SII]λ6716
[SII]λ6731
flux (1e−17 erg/s/cm²/Å)
λ (Å)
λ (Å)

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, respectivelly.
- $[\text{O III}]/\text{H}\beta$: values decrease with the distance to the nucleus.



4C +29.30 - Electron density

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