High-resolution molecular line observations of radiogalaxies

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Molecular gas makes most of the gas mass in galaxy nuclei, also in radiogalaxies!

*Most studies to date are low-resolution CO surveys, however...*

(e.g., Lim et al 2003; Prandoni et al 2007; Ocaña-Flaquer et al 2008)
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High-resolution (<1") observations in mm-λ key to mapping molecular line **emission** and **absorption** in radiogalaxies (e.g., in CSOs)

*Minimize confusion between emission and absorption in the beam*
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**Minimize confusion between emission and absorption in the beam**

**Emission** + **absorption** lines needed to provide 2D-view of molecular disks

*Interpretation of ‘only’ absorption lines hazardous: inflow? outflow?*
Molecular gas in radiogalaxies

Our project...

A molecular line study of two nearby radiogalaxies made with the IRAM Plateau de Bure interferometer (PdBI): a CSO (4C31.04) and a FRII (3C293)

- Spatial resolution: 0.′′3–1.′′2
- Frequency range: 88 GHz–230 GHz

Several species/lines adapted to probe the emission and absorption of molecular gas in the circumnuclear disks of radiogalaxies

- CO(1-0), CO(2-1), HCO+(1-0), HCN(1-0)
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**gas content**: N_{gas} , M_{gas} , distribution , kinematics?
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Gas content: \( N_{\text{gas}} \), \( M_{\text{gas}} \), distribution, kinematics?

Explore evolutionary links between different types of radiogalaxies

Are CSOs and FRII connected? Are CSOs young or frustrated sources?
CSOs: the case of 4C31.04

- CSO associated with nucleus of giant elliptical MCG 5-4-18

- Companion spiral at 20 kpc (MCG 5-4-17)

- Other fainter objects in the group.

- No signs of tidal tails or large-scale ongoing interaction.

HST optical picture (R-band) from Perlman et al 2001
CSOs: the case of 4C31.04

Prototypical CSO: compact radio source at cm-λ: ~100 pc size

- Faint point-like core
- Two extended lobes on ~20-40pc
- Expansion of lobes: 0.1pc/yr (Giroletti et al. 2003)
- No jet --> close to sky plane

VLBA image @5GHz (2mas beam) from Giovannini et al. 2001
Nucleus shows obscuration features in HST optical images.

Two cone-like nebulosities extend perpendicular to dust features on ~kpc scales.

Optical nebulosities aligned with radio axis.

Signature of gas shocked by jet? (e.g., Labiano et al. 2003)
Anatomy of the dusty nucleus: HST R-H color images

Edge-on ~1 kpc dusty disk perpendicular to radio axis.

Extended ~3 kpc spiral-like structure connected to disk.

Shell-like features around cones?

HST R-H color image from Perlman et al 2001
**4C31.04**

**HST optical pictures**

HST extinction map: how much dust/mass in 4C31.04?

- Total extinction $A_B$ image from Perlman et al 2001

- Average $A_B$ extinction = $0.5^m$

- Maximum $N(H)$ towards disk:
  
  $N(H) \sim 3 \times 10^{21} \text{cm}^{-2}$

- $M_{\text{dust}} \sim 5 \times 10^5 M_{\text{sun}}$
  
  $M_{\text{gas}} \sim 5 \times 10^7 M_{\text{sun}}$

- Consistent with HI absorption
  
  $M_{\text{gas}} \sim 10^8 M_{\text{sun}}$ at $R < 150 \text{pc}$

*(Conway 1996)*
Continuum emission detected at **1mm** (230 GHz) and **3mm** (89 GHz)
Continuum emission at 3mm hardly resolved with 1.2''x0.6'' beam

~160mJy, on AGN

S_ν \sim ν^{-α}, α\sim1-2, 89-230 GHz

non-thermal emission
A dusty disk in 4C31.04

Continuum emission at 1mm spatially resolved with 0.5″x0.24″ beam

PdBI maps

A dusty disk in 4C31.04


Continuum emission at 1mm spatially resolved with 0.5´´x0.24´´ beam

POINT-source

~40mJy, on AGN

non-thermal emission

R-H color (colour scale) + 1mm@230GHz (contours)
Continuum emission at 1mm spatially resolved with 0.5´´x0.24´´ beam

~40mJy, on AGN

~20mJy, linked to dusty disk

1”x0.1” (1.1 kpc x 0.1 kpc)-size

Truly dust emission: no free-free!
PdBI maps

A dusty disk in 4C31.04


DISK:

1-component fit (30K)
IRAS(100μm,60μm)

M_{dust} (warm) \sim 6 \times 10^7 M_\text{sun}

M_{gas} \sim a few \times 10^{10} M_\text{sun}

2-component fit (15K, 30K)
IRAS(100μm,60μm)+PdBI(230GHz)

M_{dust} (total) \sim 5 \times 10^8 M_\text{sun}

R-H color (colour scale) + 1mm@230GHz (contours)
**PdBI maps**

**A dusty disk in 4C31.04**


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**DISK:**

$M_{\text{gas}}$?

$M_{\text{gas}}(1\text{mm-continuum}) \gg M_{\text{gas}}(\text{HI})$

$M_{\text{gas}}(1\text{mm-continuum}) \gg M_{\text{gas}}(A_v)$

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*R-H color (colour scale) + 1mm@230GHz (contours)*
PdBI maps

A dusty disk in 4C31.04


M_{gas} (1mm) \sim (10-100) \times M_{gas} (HI)

M_{gas} (1mm) \sim 100 \times M_{gas} (A_v)

DISK: M_{gas} ?
Molecular gas **emission** + **absorption** in HCO$^+$J=1-0 line over $\sim$1200 km/s$^{-1}$

**HCO$^+$(1-0)** line emission and absorption towards AGN core
Molecular gas **emission** + **absorption** in HCO$^+$ J=1-0 line over ~1200 km s$^{-1}$

**Emission over ~ 950 km s$^{-1}$**
- I[-300, 25] km s$^{-1}$
- III[275, 900] km s$^{-1}$
- $n(H_2) \geq 10^4$ cm$^{-3}$

**Absorption over ~ 250 km s$^{-1}$**
- II[25, 275] km s$^{-1}$
- $n(H_2) \sim 10^3$ cm$^{-3}$

$HCO^+(1-0)$ line emission and absorption towards AGN core

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**PdBI maps**

**A molecular disk in 4C31.04**

PdBI maps

A molecular disk in 4C31.04


HCO⁺ emission is spatially resolved → an ~edge-on ~1.4 kpc rotating disk

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I[275, 900] km s⁻¹
I[-300, 25] km s⁻¹

Absorption over ~ 250 km s⁻¹
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HCO⁺ channel maps I,II,III (contours) over HST R-band (colour)
HCO\(^{+}\) emission is spatially resolved → an ~edge-on ~1.4 kpc rotating disk

Emission over ~ 950 km s\(^{-1}\)
I\([275, 900]\) km s\(^{-1}\)  : peaks NE
I\([-300, 25]\) km s\(^{-1}\)

Absorption over ~ 250 km s\(^{-1}\)
II\([25, 275]\) km s\(^{-1}\)

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Emission over ~ 950 km s$^{-1}$

II$^-[25, 275]$ km s$^{-1}$: peaks SW

Absorption over ~ 250 km s$^{-1}$

II$^[25, 275]$ km s$^{-1}$
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PdBI maps

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*HCO$^+$ channel maps I,II,III (contours) over HST R-band (colour)*
PdBI maps

A molecular disk in 4C31.04


An edge-on molecular rotating disk

HCO⁺ channel maps I,II,III (contours) over HST R-band (colour)

Position-velocity strip of HCO⁺ along A-B
PdBI maps

A molecular disk in 4C31.04


Distribution + kinematics of molecular gas are **distorted**

The disk is asymmetrical...

$I[\text{HCO}^+] \text{ (NE)} \sim 3 \times I[\text{HCO}^+] \text{ (SW)}$

The disk is tilted...

HCO$^+$ disk is tilted with respect to dust disk

$\text{HCO}^+$ emission ch-I,III (white+blue-contours) and dust-emission (black contours) over HST R-H image (colour)
PdBI maps

**A molecular disk** in 4C31.04


Distribution + kinematics of molecular gas are **distorted**

**HCO⁺ emission in ch-III (contours) and over HST R-band image**

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The disk thickens north...

Interaction with optical nebulosities?
PdBI maps | A molecular disk in 4C31.04


Kinematics: evidence of strong **non-circular motions**

- If $v_{\text{sys}}$ fitted on emission profile, absorption is $150\text{km} \cdot \text{s}^{-1}$ blueshifted with respect to $v_{\text{sys}}$
- Non-circular motions projected?

- Disk not dynamically relaxed
- Settling down after merger?
- Interacting with other phases of ISM?

**HCO^+(1-0)** line emission and absorption towards AGN core
PdBI maps


A molecular disk in 4C31.04

From HCO\(^+\) (1-0) line emission, we estimate \(M_{\text{dense-gas}}\) and \(M_{\text{gas}}\):

\[M_{\text{dense-gas}} \approx (0.5 - 4) \times 10^9 \, M_{\odot}, \quad n(H_2) > 10^4 \, \text{cm}^{-3}\]

\[M_{\text{gas}} \approx 10 \times M_{\text{dense-gas}} \approx (0.5 - 4) \times 10^{10} \, M_{\odot}, \quad n(H_2) > 10^3 \, \text{cm}^{-3}\]
Estimates from dust emission and HCO\(^+\) line emission give both:

\[ M_{\text{gas}} \sim 10^{10} \ M_{\odot} \sim \text{10-100 larger} \] than derived from HI or \( A_v \) maps.
PdBI maps


A molecular disk in 4C31.04

Estimates from dust emission and HCO$^+$ line emission give both:

$$M_{\text{gas}} \sim 10^{10} M_{\text{sun}} \text{ ~10-100 larger than derived from HI or } A_v \text{ maps}$$

Estimates from HCO$^+$ line absorption give:

$$N_{\text{gas}} \sim (0.5-1.5) \times 10^{22} \text{ cm}^{-2} \text{ ~10-100 larger than derived from HI or } A_v \text{ maps}$$
Conclusions

Discovery of a massive molecular/dusty disk fueling the nucleus of 4C31.04

\[ M_{\text{gas}} \sim 10^{10} M_{\text{sun}} \ (M_{\text{mol}} >> M_{\text{HI}}) \]

\[ M_{\text{gas}} [4C31.04] \sim M_{\text{gas}} [\text{ULIRGs}] ! \]
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The bulk of the gas is in rotating disk perpendicular to jet
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\textit{Settling down after merger or interacting with other phases of ISM?}
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Work in progress….

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VLBI mapping of molecular absorption in 4C31.04

Comparison between CSOs and FRII: observations of 3C293
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