AGN-driven turbulence revealed by extreme [CII]158µm line cooling in radio-galaxies

Pierre Guillard
CNES Fellow
Institut d’Astrophysique Spatiale, Orsay, France

“The Universe Explored by Herschel”, ESTEC, Noordwijk, October 15th 2013

with: Nicole Nesvadba (IAS), Patrick Ogle (IPAC), François Boulanger (IAS), Matt Lehnert (IAP), Phil Appleton (NHSC), Bjorn Emonts (CSIRO), Pierre Lesaffre (ENS/LERMA), Michelle Cluver (SSC), Guillaume Pineau des Forêts (IAS, LERMA), Edith Falgarone (ENS/LERMA), Raphaella Morganti (SRON)
- AGN feedback…sure, but with which efficiency ???

- Physical state of the molecular gas in radio-galaxies: lessons from Herschel and insights into the physics of feedback

- [CII] as a tracer of low pressure, warm, non star-forming H$_2$ gas (too diffuse to be bright in CO)
Feedback is needed to make galaxy growth inefficient…

Dual role of AGN feedback:
- High redshifts: quenches the initial starburst associated with early phases of galaxy formation
- Low redshifts: complements SN feedback to suppress gas cooling and prevent gas accretion

"Too many small galaxies, too many big galaxies in the nearby universe, too few massive galaxies at high redshift, too many baryons within the galaxy halos."

AGN feedback seems an appealing solution…
AGN feedback is needed to make galaxy growth inefficient…
But why what efficiency??

HERSCHEL IR/SUB-mm = RED/YELLOW
XMM-Newton X-rays = BLUE

ACCRETION:
gravitational energy input

AGN FEEDBACK
Thermal energy (X-ray plasma)
Bulk gas motions: outflows, superwinds, …
turbulence

ACCRETION:
gravitational energy input

Cen A
AGN feedback is needed to make galaxy growth inefficient…
But why what efficiency??

HERSCHEL IR/SUB-mm = RED/YELLOW
XMM-Newton X-rays = BLUE

ACCRETION:
gravitational
energy input

AGN FEEDBACK

Thermal energy (X-ray plasma)
Bulk gas motions: outflows, superwinds, …

Turbulence in H$_2$ gas

Role of Turbulence in galaxy formation?
Impact on the molecular gas? On the SFE?
Why observing [CII] in radio-galaxies with Herschel?

Advantages of radio-galaxies: we can estimate
- Their jet mechanical power
- The spatial scales of energy dissipation: up to Mpc!

Multi-wavelength observations of powerful radio-galaxies:
- X-rays
- HI, NaD: outflow signatures, mass outflow rates
- CO(1-0)
- Spitzer mid-IR spectroscopy ($H_2$/PAH: kinetic vs UV heating)
- Herschel far-IR spectroscopy:
  [CII] 158 µm, $\Delta E/k = 91$K. Probes WNM > CNM transition (30 – 10^4 K)

Observations provide access to the physical conditions of the gas and the way kinetic energy dissipates in the different ISM phases, including the molecular gas
The 3C 326 radio galaxy: one of the best example of negative jet-driven feedback

- Pair of galaxies 3C326N & S at $z=0.089$
- Both contain nuclear radio sources. Which creates the jets? (Rawlings+90)

Ogle et al. 2007
J.P. Leahy et al.

3-color Spitzer IRAC image
VLA 1.4 GHz image

2 Mpc

NORTH
SOUTH
Warm H$_2$ gas in the 3C 326N radio galaxy

- Pair of galaxies 3C326N & S at $z=0.09$
- Both contain nuclear radio sources. Which creates the jets? (Rawlings+90)

- $L(H_2) = 8 \times 10^{41}$ erg/s
- $2 \times 10^9$ M$_\odot$ of warm H$_2$
- 3kpc turbulent H$_2$ disk (Nesvadba+11)

- SFR $< 0.07$ M$_\odot$ yr$^{-1}$
- $L(H_2)/L(\text{IR}) \sim 0.2$ !!

Ogle et al. 2007
Evidence for suppression of star formation

Nesvadba et al. 2010, Guillard et al. 2012b
Powerful [CII] line but weak UV and star formation!

Mass of [CII]-emitting gas: $1.5 \times 10^9 \, \text{M}_\odot$

at $n_H = 100 \, \text{cm}^{-3}$ and $T=100 \, \text{K}$

The warm molecular gas is the only gas reservoir that can account for the [CII] emission
Powerful [CII] line but weak UV, CO and star formation!

Mass of [CII]-emitting gas: $1.5 \times 10^9 \, M_\odot$

at $n_H = 100 \, \text{cm}^{-3}$ and $T=100 \, \text{K}$

The warm molecular gas is the only gas reservoir that can account for the [CII] emission

 Weak CO emission. [CII] / CO(1-0) = 4000
[CII] emission in star-forming galaxies

Stacey+10
Enhanced [CII] emission

Star formation heating

Turbulent Heating?

Stephan’s Quintet (Appleton+13)

3C 326 (Guillard+ in prep)

Taffy Bridge

HCG57D (Alatalo+ in prep)

Taffy Galaxies (Peterson+ in prep)
[CII] emission as a probe of warm diffuse H$_2$ gas in AGN hosts

- C$^+$ cooling rate for a molecular fraction of 90%, and solar abundance (40% in gas phase)
- Dust model (Compiègne+10) for $I_{250\mu m}$
- Pressure $\sim 10^5$ K cm$^{-3}$ for 3C 326
- Weak [OI] emission implies $T<300K$ and $n_H \leq 5\times10^3$ cm$^{-3}$ (Guillard +13a)
- No detection of high-J CO lines.
What is the gas heating source?

Cosmic Rays?

- $\zeta = 2 \times 10^{-14} \text{s}^{-1}$ required to balance the observed [CII]+$\text{H}_2$ cooling rate (line luminosity to mass ratio).

- Energetically possible

- The gas has to be denser than $n_H \approx 10^4 \text{ cm}^{-3}$ to remain molecular

- [CII]/[OI] > 2.2 and weak CO lines do not favor this solution

- But... CRs could be responsible for high C$^+$/CO abundance in $\text{H}_2$ gas (Mashian+13)
What is the gas heating source?

Turbulent heating?

- 10% of the jet mechanical power (a few $10^{44}$ erg s$^{-1}$) is enough to drive the outflow and power the observed H$_2$ luminosities (Nesvadba+10)

- turbulent heating is energetically possible if:

$$\Gamma_{turb} = \frac{3}{2} M_{H_2} \frac{\sigma_{turb}^3}{H} > L_{[CII]} + L_{H_2}$$

$$L(C^++H_2)/M(H_2) = 0.50 \, L_\odot/M_\odot$$

$$\sigma > 180 \, \text{km/s for } H = 3 \, \text{kpc.}$$

Observations: $\sigma = 200-250 \, \text{km/s}$

from [CII] and near-IR H$_2$ (Nesvadba+11)
What is the gas heating source?

Turbulent heating?

- 10% of the jet mechanical power (a few $10^{44} \text{ erg s}^{-1}$) is enough to drive the outflow and power the observed $\text{H}_2$ luminosities (Nesvadba+10)

- Turbulent heating is energetically possible if:

$$\Gamma_{turb} = \frac{3}{2} M_{\text{H}_2} \frac{\sigma_{turb}^3}{H} > L_{\text{[CII]}} + L_{\text{H}_2}$$

$L(\text{C}^+ + \text{H}_2)/M(\text{H}_2) = 0.50 \ L_\odot/M_\odot$

$\sigma > 180 \text{ km/s for } H = 3 \text{ kpc.}$

Observations: $\sigma = 200-250 \text{ km/s}$

from [CII] and near-IR $\text{H}_2$ (Nesvadba+11)
Turbulence as a feedback mechanism? A non self gravitating disk in 3C 326N

Pressure equilibrium (self-gravitating disk, stellar spheroid)

\[ H \approx \frac{2}{\pi G} \frac{\sigma_{\text{gas}}^2}{\Sigma_{\text{gas}}} \]

Turbulent heating rate > Cooling rate

\[ \frac{3}{2} \frac{\sigma_z^3}{H} = \epsilon^{-1} \frac{L_{\text{[CII]} + \text{H}_2}}{M_{\text{H}_2}} \]

The \( \text{H}_2 \) gas is not gravitationally bound on the physical scale of the disk → Low SFE
3C 326N is not a « one-off »

Bright (2 \(-\ 18 \times 10^{-17} \ \text{W/m}^2\)) and very broad (400 \(-\ 1200 \ \text{km/s}) \ C^+ \text{ line with complex, asymmetric profiles (Guillard et al. in prep.)}.

All these galaxies also show shock-excited rotational lines of \text{H}_2\ in the mid-IR (Guillard+12)
Extreme C^+ / PAH ratios: [CII] as a tracer of non star-forming gas

Stephan’s Quintet (Appleton+13) + other galaxy interactions (Taffy, HCGs)

Diaz-Santos, Armus et al., 2013

Photoelectric heating

Guillard et al. 2013, sub.
Enhancement of $C^+$ emission by turbulence?

Stephan’s Quintet (Appleton+13)

Guillard+13a

GOALS
Diaz-Santos, Armus et al. 2013
Conclusions

- Discovery of kinematically-broad C$^+$ line emission in powerful radio-galaxies, too bright to be excited by star-formation alone.

- [CII] traces non star-forming warm H$_2$ gas, too diffuse to be bright in CO.

- The dissipation of mechanical energy (jet) is the most likely heating source. Cosmic rays play an important chemical role (high C$^+$/CO abundance in low A$_V$ gas).

- Turbulent heating has a very important impact on the physical state of the molecular gas and can prevent the H$_2$ gas to be bound on disk scales.

- Towards an understanding of how the mechanical energy is dissipated and re-distributed among thermal/bulk/turbulent components... Crucial to understand the suppression of star formation (negative feedback) in early galaxy formation. Input for galaxy formation models!