Impact of relativistic jets on the ISM of their host galaxy

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with
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AGN feedback and galaxy

- AGN feedback crucial to match galaxy mass function
- Can be in the form of winds (Quasar mode/Establishment mode)
Some basic questions

- What is the effect of relativistic jets at galactic scales?
- Over what scales? Do the jets affect just a narrow channel or a wider region?
- Outflow? or turbulence? (both)
- How is SFR regulated? Is it ejective (outflows)? Preventive (turbulence)? Passive evolution (strangulation?)? (all?)
- What are the observational signatures of jet-ISM interaction?
The set up

We perform simulations (with PLUTO) of 3D relativistic jets from AGNs interacting with a turbulent ISM

- **Turbulent ISM**: fractal log normal density distribution with Gaussian velocity dispersion (values similar to forster-schreiber et al 2009).

- Different ISM densities, morphology (disk + spherical), jet power.

- Domain size $\sim 5\text{kpc}$, resolution $\sim 6\text{pc}$. External gravity (DM+Baryons). Atomic cooling via MAPPINGS V.
### Simulation list

#### Spherical gas distribution

<table>
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<th>No</th>
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<th>Density (n_w_0, in cc)</th>
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Densities: n_w_0 = 150-2000 cm\(^{-3}\)

Power = 10\(^{44}\) - 10\(^{46}\) ergs\(^{-1}\)

#### Disks

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Densities: n_w_0 = 100-400 cm\(^{-3}\)

Power = 10\(^{45}\) - 10\(^{46}\) ergs\(^{-1}\)

Θ = 0, 20, 45, 70

#### IC 5063

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Gas mass ~ 10\(^8\)-10\(^{10}\) M_☉
The dentist drill in spherical gas distribution

Jets couple strongly with host's ISM.

Launch **fast multiphase outflows** but not enough to escape.

**Low power jets are important!** Couple more with the ISM, will induce more turbulence and more numerous!

Gas distribution spherical. Easier to couple. **Disks?**

Mukherjee et al. 2016, 2017
Feedback in disk galaxies

- Central outflow < 1 kpc
- Compression & shocks on outer edges

\[ P_{\text{jet}} = 10^{45} \text{ergs}^{-1} \]

\[ \beta = 0.4c, 0.9c \]
Feedback in disk galaxies

$P_{\text{jet}} = 10^{46} \text{ergs}^{-1}$

Temperature (Log$_{10}(T)$) at time: 0.00 Myr

Velocity ($V_\text{r}/100 \text{ km s}^{-1}$) at Time: 0.00 Myr

arXiv:1803.08305
Early evolution:

- A sharp increase in dispersion of shocked gas with radius, traces evolving bubble.

Late times:

- Velocity dispersion is increased by several times its initial value throughout the disc, up to 300-400 km/s⁻¹.

- Depends on jet power, ISM density $n_w: 100, 200, 400$ cm⁻³, jet power $P_j: 10^{45}, 10^{46}$ erg s⁻¹.
Inclined jets

- Inclined jets couple more with turbulent disc
- More clouds are lifted off the disc
- The cavity is filled with ablated thermal gas + non-thermal plasma
Inclined jets

Log(n) at time: 0.00 Myr

Inclined at 45°

3C 293
Mahony et al. 2016

NGC 3079
Cecil+01, Veilleux+ 99

Dopita et al. 2015
IC 5063 has a jet going through its disk. Multiwavelength observations (ALMA, HST, VLT) show shock excited outflowing gas.
Inclined jets: IC 5063

Mukherjee et al. 2018, arXiv:1801.06875
Inclined jets: IC 5063

- The overall increased dispersion matches ALMA obs, indicates clearing due to expanding bubble.
- Spiky features in the PV is reproduced, indicates jet interaction with clumpy ISM.
- $P = 10^{45}$ erg s$^{-1}$ jet has increased dispersion, and non-uniform PV.

Mukherjee et al. 2018, arXiv:1801.06875
Quenching via turbulence?

**Velocity dispersion with time**

- Sim. G: $10^{46}$ erg s$^{-1}$
- Red: $T > 10^4$ K
- Blue: $T < 10^4$ K
- Green: all gas

**Increase in velocity dispersion**

- A: $P_{\text{vir}}$, $n_{\text{vir}}=100$, $t = 0.5$ Myr
- B: $P_{\text{vir}}$, $n_{\text{vir}}=200$, $t = 0.5$ Myr
- C: $P_{\text{vir}}$, $n_{\text{vir}}=200$, $t = 0.3$ Myr

**3C 326 (and MOHEGS)**

Nesvadba et al. 2010, 11

**NGC 1266**

Alatalo et al. 2011, 15
Positive feedback?

Density enhancement due to radiative shocks

- Jets with $P=10^{46} \text{ erg/s}$ show a significant enhancement.
- Inclined jets couple more, higher enhancement.
- Low density ISM show a decline after an initial increase.
Star formation surface density?

\[
\text{SFRD} = \int (\rho / t_{\text{ff}}) dz
\]

\[
P: 10^{46} \text{ erg s}^{-1}, \Theta = 0
\]

\[
\text{SFR} = \epsilon_{\text{SFR}} (\rho d^3 x) / t_{\text{ff}}
\]

\[
t_{\text{ff}} = (3\pi / (32 G \rho))^{1/2}
\]
Star formation surface density?

\[ SFR = \epsilon_{SFR} (\rho d^3 x) / t_{ff} \]

\[ t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} \]

\[ SFRD = \int (\rho / t_{ff}) dz \]
Concluding...

★ Jets launch **fast multiphase outflows** over **several kpc** but not enough to escape.

★ **Low power jets are important!** Couple more with the ISM, will induce more turbulence and more numerous!

★ Jets make **disks turbulent. Inclined** jets more.

★ SFR will be regulated by shocks from the energy bubble and turbulence, rather than mass ejection. **Initial SFR burst** possible.

**Thank you!**
Inclined jets: IC 5063

- The overall increased dispersion matches ALMA obs, indicating clearing due to an expanding bubble.
- Spiky features in the PV indicate jet interaction with clumpy ISM.
- Jet has increased dispersion and non-uniform PV.

Mukherjee et al. 2018, arXiv:1801.06875
Simulation list

Spherical gas distribution

Densities: $n_{w0} = 150-2000 \text{ cm}^{-3}$

Power = $10^{44} - 10^{46} \text{ ergs}^{-1}$

Gas mass $\sim 10^{9}-10^{10} M_\odot$

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Disks

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$\theta = 0, 20, 45, 70$

Gas mass $\sim 10^{9}-10^{10} M_\odot$

<table>
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<tr>
<th>Simulation Label</th>
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Wide-angled sub-relativistic outflow

- Launch vertical sub-relativistic wide-angles outflow along the minor axis (chimney effect)