Simulating the jet-ISM interaction in CSS-GPS galaxies

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In Collaboration with
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Some basic questions

- Two feedback modes in literature: **Quasar vs radio. Oversimplifies impact of jets.**

- **Young/trapped/slow** jets interact with the host’s ISM. Many examples of jet-ISM interaction.

- Radio mode can have the effect of quasar mode, blending the two.

- How is **star-formation rate** regulated by direct interaction?

- Impact on **circum-galactic gas**

**Simulations on two scales:**
- Jets inside the galaxy's potential ~ 5 kpc -> focus on jet-ISM feedback
- Intermediate length scales 10-20 kpc -> Focus on jet dynamics & non-thermal emission

**Relativistic jets with PLUTO RMHD code**
~ 20 M CPU hrs and counting
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Jet-ISM Simulations

**Spherical gas distribution**

Densities: nw\(_0\) = 150-2000 cm\(^{-3}\)

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

**Disks**

Densities: nw\(_0\) = 100-400 cm\(^{-3}\)

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

\(\Theta = 0, 20, 45, 70\)

Gas mass ~ 10\(^9\)-10\(^{10}\) M\(_\odot\)
A Multi-phase ISM

Multiphase ISM and multiphase outflows:

1. Dilute hot energy bubble
2. Shocked dense \((n > 100 \text{ cm}^{-3})\) outflowing gas at \(>100 - 300 \text{ kms}^{-1}\)
3. Less dense \((n \approx 1-10 \text{ cm}^{-3})\) fast flowing \((>1000 \text{ kms}^{-1})\) from sheared cloud material
4. Low power jets remain confined. Less effective in outflow, but shock heats the ISM.

Movie: \(\text{https://youtu.be/Fh5819VkQyw}\)

Mukherjee+2016,2017
Negative feedback: Mass loss

Not enough gas ‘escapes’, depends on density of clouds and jet power.

Galactic Fountains!
The spectra transition from a GPS to a CSS as the jet evolves to larger scales.

**Pro:** The sims follows the turnover-linear size correlation for some ranges of length scales and reasonable densities.

**Con:** Depends on the extent of the gas distribution. Our sims: have dense gas ~ 2-3 kpc. So it fails for larger sizes.

**Movie:** https://youtu.be/2GjKKAP_6J0
Jet-disk interaction

- Inclined jets couple more with turbulent disc.
- Backflow from the jet impacts a much larger part of the disc and engulfs it.
- Local outflows are launched at points of direct interaction

Movie: https://youtu.be/8eeKSc9_AJQ
Gemini observations of Jet-ISM interaction in 4C 31.04

Radio jet ~ 100 pc

Fell ~ 300 pc

Warm H2, shocked, ~\(10^4\) K, ~2 kpc;
blue shifted by \(100\) km s\(^{-1}\)
Observable emission features

Jets induce shocks, can be observable in emission lines.

Increased dispersion perpendicular to jets.

Meenakshi, DM + in prep
Photoionisation using CLOUDY

Perpendicular jet $0^\circ$

Inclined jet

Ionisation cone

Partial obscuration

Jet opens up new lines of sight
Inclined jets: IC 5063

Mukherjee+2018a

Position-velocity

Morganti+2015a
Estimating SFR with improved subgrid physics

**Standard approaches:**

$$\text{SFR} = \frac{M}{t_{ff}} \text{ for } \rho > \rho_{\text{threshold}}, \quad t_{ff} \propto \rho^{-1/2}$$

No input about **turbulent velocity dispersion** or **Mach number**.

**Better option:** Use a turbulence based SFR prescription (Krumholz+2005, Federrath+2012).
Estimating SFR

- Early times: SFR efficiency decreases, increase in turbulent dispersion (-ve feedback).
- But, shocks increase density.
- Later times: turbulence decays, enhanced density raises efficiency again (+ive feedback)

\( \theta_j \): angle between jet axis and disk-normal

Mandal, DM + in prep
Jet feedback & SFR efficiency

- Positive feedback may not mean strong enhanced of SFR efficiency. **Inefficient positive feedback.**
- Positive & negative feedback can happen in the same system.
- Depends on many other factors: jet power, ISM density, jet-ISM coupling

Nesvadba, GVB, DM+2020
Jets with new hybrid particle + fluid scheme

Spatial evolution:

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{v}(\mathbf{x}_p)$$

Spectral evolution:

$$\mathcal{N}(p, \tau) = \int d\Omega p^2 f_0 \approx 4\pi p^2 f_0, \quad \frac{d\mathcal{N}}{d\tau} + \frac{\partial}{\partial E} \left[ \left( -\frac{E}{3} \nabla_\mu u^\mu + \dot{E}_l \right) \mathcal{N} \right] = -\mathcal{N} \nabla_\mu u^\mu$$

Energy losses, synchrotron, inverse compton

**DSA model for acceleration at shocks**

Finally:

$$J'_{\text{syn}}(\nu', \hat{n}'_{\text{los}}, B') = \frac{\sqrt{3}e^3}{4\pi m_e c^2} |B' \times \hat{n}'_{\text{los}}| \int_{E_i}^{E_f} \mathcal{N}'(E') F(x) dE'$$
Jets with new hybrid particle + fluid scheme

- Particles get energized at shocks.
- Shocks inside the jet spine, jet-head and cocoon
- Complex trajectories

Mukherjee+2020, Mukherjee+2021

Particle color = Max energy, indicates shocks

Movie: https://youtu.be/bpFa22hjTSA
Internal shocks in turbulent cocoon

- Multiple internal shocks which can re-accelerate electrons in the backflow.
- Goes against the standard paradigm of a terminal hotspot and free-stream
- Turbulent cocoons have more shocks

Turbulent cocoon

Less turbulent jet

Turner & Shabala 2015
CRE Re-acceleration

- Mixing of CREs with different shock histories in turbulent cocoon
- CRE spectrum has imprints of different pops. Not just a power-law with cut-off.
- Electron spectrum varies with region.
- Internal shocks reflected at synchrotron at higher frequencies

Mukherjee+ in prep
Within the galactic potential jets couple strongly with host's ISM

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

Both turbulence (-ive) and compression (+ive) may affect SFR. Net mass-loss/ejection difficult.

Turbulence in unstable jets can re-accelerate non-thermal electrons at complex shocks.
Estimating SFR with improved subgrid physics

**Standard approaches:** \( \text{SFR} = \frac{M}{t_{\text{ff}}} \) for \( \rho > \rho_{\text{threshold}} \), \( t_{\text{ff}} \propto \rho^{-1/2} \)

No input about turbulent velocity dispersion or Mach number.

**Better option:** Use a turbulence based SFR prescription (Krumholz+2005, Federrath+2012).

- Identify potential star forming clumps using a clump-finder.
- Find intra-cloud statistics: velocity dispersion, Mach number.
- Compute SFR of each clump assuming a turbulence driven SFR model.
Unstable jets
Non-thermal emission from jets: Particle module in PLUTO

**Webb 1989**

\[
\nabla_\mu (u_\mu f_0) + \frac{1}{p^2} \frac{\partial}{\partial p} \left[ -\frac{p^3}{3} f_0 \nabla_\mu u_\mu + \langle \hat{p} \rangle_I f_0 \right] = 0.
\]

**Spatial evolution:**

\[
\frac{d\mathbf{x}_p}{dt} = \mathbf{v}(\mathbf{x}_p)
\]

**Spectral evolution:**

\[
\mathcal{N}(p, \tau) = \int d\Omega p^2 f_0 \approx 4\pi p^2 f_0.
\]

\[
\frac{d\mathcal{N}}{d\tau} + \frac{\partial}{\partial E} \left[ \left( -\frac{E}{3} \nabla_\mu u_\mu + \dot{E}_l \right) \mathcal{N} \right] = -\mathcal{N} \nabla_\mu u_\mu
\]

**Ignore:**
- Spatial diffusion
- Shear
- Diffusion in momentum space, Fermi 2\textsuperscript{nd} order

Energy losses, synchrotron, inverse compton

**Vaidya et al. 2018**

\[
\dot{E}_l = -c_r E^2
\]

\[
c_r = \frac{4 \sigma_T c \beta^2}{3 m_e^2 c^4} \left[ U_B(t) + U_{rad}(E_{ph}, t) \right]
\]

\[
J_{syn}'(\nu', \hat{n}'_{los}, B') = \frac{\sqrt{3} e^3}{4\pi m_e c^2} \left| \mathbf{B}' \times \hat{n}'_{los} \right| \int_{E_i}^{E_f} \mathcal{N}'(E') F(x) dE'
\]
Modelling Diffusive Shock Acceleration (Fermi I)

\[ N_d(p) = q \int_{p_0}^{p} \left( \frac{p}{p'} \right)^{-q+2} N_u(p') \frac{dp'}{p'} + bp^{-q+2} \]

\[ N_d(p) = \int_{p_0}^{p} F_{\text{DSA}}(p, p') N_u(p') \frac{dp'}{p'} + bp^{-q+2} \]

Subluminal

\[ q = \frac{3\beta'_1 - 2\beta'_1 \beta'_2 + \beta'^3_2}{\beta'_1 - \beta'_2} = q_{\text{NR}} + \left( \frac{1 - 2r}{r - 1} \right) \beta'^2_2 \]

Superluminal

\[ q = q_{\text{NR}} + \frac{9}{20} \frac{r + 1}{r(r - 1)} \eta^2 \beta'^2_1 \]

Drury 1983

Keshet & Waxman 2005

Takamoto & Kirk 2015
Modelling Diffusive Shock Acceleration (Fermi I)

Maximum energy of shocked electrons

\[ t_{\text{sync}} = \frac{\gamma m_e c^2}{P_{\text{sync}}} \quad t_{\text{acc}} = 2\pi a_{\text{acc}} \frac{\gamma m_e c}{eB} = a_{\text{acc}} \frac{2\pi}{\omega_g} \]

\[ a_{\text{acc}} = \frac{\eta r}{\beta_1^2 (r - 1)} \left[ \cos^2 \theta_{B1} + \frac{\sin^2 \theta_{B1}}{1 + \eta^2} + \frac{r B_1}{B_2} \left( \cos^2 \theta_{B2} + \frac{\sin^2 \theta_{B2}}{1 + \eta^2} \right) \right] \]

\[ r_L = \frac{\gamma m_e c^2 \beta_\perp}{eB} \quad \gamma = \frac{\text{MIN}(\delta x / 2)eB}{m_e c^2 \beta_\perp} \]

\[ J'_{\text{syn}}(\nu', \hat{n}'_{\text{los}}, B') = \frac{\sqrt{3} e^3}{4\pi m_e c^2} |B' \times \hat{n}'_{\text{los}}| \int_{E_i}^{E_f} \mathcal{N}'(E') F(x) \, dE' \]