Jet Feedback in High-Redshift Galaxies

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Introduction
Jet – galaxy interaction via backflow
3D AMR simulations of jet – disk interaction
  • Jet asymmetries as result of feedback?

most results:
VG, Krause, Camenzind 2009
VG, Khochfar, Krause (to be submitted)
Large-scale Feedback

- X-ray cavities observed, inflated by jet, can estimate jet powers from enthalpy or bow shocks
- Cooling flows: cavity-derived power can mostly suppress cooling
- Heating the X-ray gas also works in simulations
- Great, seems to be working mostly!
Galaxy-scale Feedback

- Impact of Jet Feedback on galaxy evolution (cosmo sims)
  - currently used modelling to simple and unphysical
  - examine details of jet – galaxy interaction

- What gas phase receives the jet power / heating?
  - hot phase (10^6-7 K): probably (as on large scales)
  - cool (dense) gas: unclear!

- But this is a crucial question:
  - effect on star formation only if cold gas changed

- Now: interaction via backflow...
Positive vs. Negative Feedback

- **Negative feedback:**
  - Ambient hot gas heated by bow shock
  - Inflation of a very hot cocoon (high entropy)
  - Stop cooling flows
  - Quench star formation
  - Important:
    - want feedback on *cold* gas, X-ray gas not so critical

- **Positive feedback:**
  - Dense clouds compressed, radiative shocks, pre-existing clouds collapse
  - Trigger/enhance star formation
  - To what extent does it work?
Jet – Galaxy Interaction

- well-collimated beams
- only minor interaction with galaxy once they broke out???

Cyg A @ 5 GHz
Perley+ 1984

(optical: HST/Fosbury, overlayed with giant elliptical M87)
Jet – Galaxy Interaction

- well-collimated beams
- only minor interaction with galaxy once they broke out???

Cyg A @ 5 GHz
Perley+ 1984

Cyg A @ 327 MHz contour overlay
Lazio+ 2006
(also: new images from LOFAR, poster)

No!
Whole galaxy contained in cocoon
Feedback possible also for large sources!
Cocoon Turbulence

- strong backflow
- highly turbulent cocoon
- interaction with ISM!
- multi-phase turbulence in cocoon (Krause & Alexander 2007)

Krause & Alexander 2007
VG, Krause, Camenzind 2009
Cocoon Turbulence

- travelling sound waves in shocked ambient gas
- weak bow shock softly turns into sound wave!
- further dissipation / heating at larger scales?
Magnetic Field Amplification in Jets

- Shearing:
  kinetic $\rightarrow$ magnetic
  (cf. Gaibler+ 2009)
  amplifies fields much beyond flux conservation!

- Strong magnetic fields in cocoon:
  suppresses entrainment
  (changes hot/cold phase mix in cocoon)

3D field lines in jet beam

M2 @ 1.3 Myr
Example of Jet-Galaxy Interaction: High-z Radio Galaxies

- Extended Emission Line Regions aligned with jets
- Outflows
- Highly turbulent motion (~1000 km/s)
- Interaction in central part although source is already larger

- Interaction with ISM via backflow vs. direct jet – ISM interaction

3 sources in Nesvadba+ 2008
3D Interaction Jet – Disk
Interaction with a Galactic Gaseous Disk

- 3D simulations with RAMSES (R. Teyssier et al.)
  Cosmological Adaptive Mesh Refinement MHD code

- *Here:*
  simulation box of $(128 \text{ kpc})^3$, 60 pc resolution
  $(2048^3 \text{ effective resolution})$
  *High redshift scenario*

- Clumpy and massive exponential disk:
  $10^{11} M_{\odot}$
  embedded in hot atmosphere ($10^7 \text{ K}$),
  cooling important,
  $10^4 \text{ K minimum temperature},$
  jet power $5 \times 10^{45} \text{ erg/s}$
Jet – Disk Interaction

- Jet injected at $t = 2$ Myr
- Jet bores through disk
  - Blastwave clears central region, except a disk-like compressed structure
  - Jet beam propagates through dense clumps of gas, asymmetry arises
- Density evolution as movie (volume rendering):
  - dense gas: blue
  - diffuse (hot) gas: yellow, red
movies available at:
http://www.mpe.mpg.de/~vgaibler/jet-disk/
ISM causing Jet Asymmetries?

- First step: do we understand the asymmetries in the hydro simulation?

- Monte Carlo simulation:
  - considerable jet – ISM interaction will cause propagation delay
  - asymmetries may give insight into feedback
  - “detect” clumps even after their destruction (as statistical delay)

- Model: 1D momentum balance for jet propagation

\[ \hat{v}_h \approx \left( \frac{\rho_j}{\rho} \right)^{1/2} v_j \]

\[ t = \frac{1}{\rho_j^{1/2} v_j} \int_{x'}^x \rho(x')^{1/2} \, dx' \]

- Examine link between clumpy ISM properties and asymmetries...
ISM causing Jet Asymmetries?

- Disk height
- Disk density
- Density variation

Graphs showing probability density, time delay between jets, disk height, disk density, and density variation.
ISM causing Jet Asymmetries?

- Asymmetries in hydro simulation even stronger than 1D estimate (complex effects of early blast wave and then beam propagation)

**density**

**pressure**
High-z Emission Line Nebulae

- Observations?
- McCarthy+ 1991: extended emission line regions of HzRG are brighter on the side of the closer lobe
  Interpretation: environment causes arm length asymmetries
- This is actually seen in our simulations...
ISM causing Jet Asymmetries?

- Observed asymmetries: ~ 10 kpc
- Could be explained by $10^9 - 10^{10} M_{\odot}$ of gas
- Local radio galaxies: few $10^8 M_{\odot}$ (molecular) median, some much more
- Inner regions: gas may be destroyed by jet (cf. hydro simulation of $10^{11} M_{\odot}$)
- Asymmetries: a sign of feedback!

Ocana Flaquer+ 2010
Next steps...

- Effect on galactic star formation

- Kinematics
- Energetics:
  - jet impact on different gas phases, thermal, kinetic (outflows)
Jet feedback seems to be working for cosmological simulations, although very simplistic recipe.

Jet break-out and cocoon turbulence may have strong impact on galactic gas.

Actual jet physics for multi-phase gas quite complex... Quantitative numbers of 3D interaction coming now.

HzRG emission line regions and jet asymmetries may show jet feedback at work.