ENIGMA Cork MHD
III. Application
MHD Jet Simulations

Max Camenzind
[Martin Krause, Volker Gaibler]
LSW Königstuhl, ZAH
Do we understand Cygnus A?

Not at all!

Lorentz factor = 1.04, v_J = 0.28 c, Mach = 6

[ Hughes 1996 ] 6 ppb
Bow shock in Cyg A is a weak shock !!!

\[ V_{\text{Head}} = V_{\text{Beam}} \frac{\sqrt{\eta}}{1 + \sqrt{\eta}} ; \ M \gg 1 \]

\[ \eta = \frac{\rho_B h_B \Gamma_B^2}{\rho_G} : \text{density contrast} \]

\[ V_{\text{Beam}} = 100 \frac{\text{kpc}}{\text{Myr}} \sqrt{10^{-4} \frac{\text{V}_{\text{Head}}}{\eta}} \frac{\text{kpc}}{\text{Myr}} \]

Bow shock in Cyg A is a weak shock !!!

\[ c = 307 \frac{\text{kpc}}{\text{Myr}} ; \ c_{S,Gas} = 0.6 \frac{\text{kpc}}{\text{Myr}} \]
Magnetic Jets have much more parameters.

Fundamental Plane for Jets

Mach number

\[10^2\]

\[10\]

\[1\]

\[10^{-5}\]

\[10^{-4}\]

\[10^{-3}\]

\[10^{-2}\]

\[10^{-1}\]

\[1\]

\[10\]

\[10^2\]


CHH Jets

HH Jets

FR II Jets

FR I Jets

1138-262

Cyg A

3C273

Magnetic Jets have much more Parameters
Almost 50 years ago, George Herbig and Guillermo Haro independently discovered a number of compact nebulae with peculiar spectra near dark clouds.

The large range of excitation conditions requires bow shocks and other complex morphologies. By the early 1980s, several Herbig-Haro (HH) objects were shown to be highly collimated jets of partially ionized plasma moving away from young stars at speeds of 100 to over 1000 km/s (R. Mundt, MPIA Heidelberg; Bo Reipurth at ESO).
Pulsed Hydro-Jet (Popular Model)

Overpressured Magnetic Jet (LSW Model; Camenzind 1990)

Homogeneous Cloud

Turbulent Cloud
Closed Magnetic Structure

Thiele & Camenzind 2001
Pinch & Kink Instabilities

Div(B) = 0
All field lines are closed!
2) How does the IGM change by the jet impact? It depends ...

Basic parameter: the density contrast jet / IGM \( \eta \)

**Constraints:**
- Non-relativistic jet
  \[
  L = \pi r_j^2 \rho_j v_j^3 \\
  \eta = \frac{\rho_j}{\rho_0} \\
  \rightarrow \eta = 6 \times 10^{-3} L_{47} r_{kpc}^{-2} \left( \frac{n_0}{0.2 \text{ cm}^{-3}} \right)^{-1} \left( \frac{v}{0.5c} \right)^{-3}
  \]
- Relativistic jet
  \[
  L = 2 \pi r_j^2 \rho_j \Gamma (\Gamma h - 1) \beta c^3 \\
  \eta = \Gamma^2 h \rho_j / \rho_0 \\
  \rightarrow \eta = 4 \times 10^{-4} L_{47} r_{kpc}^{-2} \left( \frac{n_0}{0.2 \text{ cm}^{-3}} \right)^{-1} \beta^{-1}
  \]
Essentials

- Cluster gas properties are essential for understanding their JETs (density contrast and profile, temperature, magnetic fields);
- Low $\eta$ Jets $\rightarrow$ 3 Phase Model of JET evolution: From the Sedov-phase over the cigar-phase towards the bubble-phase;
- Do we now understand Cygnus A?
- The Bubble-Phase of JET-activity is now a very active field of research (Perseus).
Cluster Evolution

- Clusters form in the high density peaks of cosmic density perturbations (M. White et al. 2001; Millenium Run 2005).
- Standard cosmology: LCDM Parameters:
  - $0.67, 0.3, 0.7, 0.040, 1$
  - $200 \times 200 \times 33$ Mpc
- Gas distribution ->
Temperature vs Cluster Mass
SIDM?

\[ \gamma = \frac{4}{3} \]
\[ \alpha = 1 \]
\[ \nu = 3 \]

← JET Propagation →

\[ \delta_c = \frac{200}{3} \frac{c^3}{\left[ \ln \left( 1 + c \right) - 1 \right]} \]

\[ \frac{\rho_d}{\rho_{\text{crit}}(z)} = \frac{\delta_c}{\left( \frac{r}{r_s} \right)^\gamma \left( 1 + \left( \frac{r}{r_s} \right)^\alpha \right)^{(\nu - \gamma)/\alpha}} \]
Typical Density Profile in a Cluster (Hydra, CXO)

- Used to determine total cluster Mass

- Input for Jet Simulation

\[ M_{\text{tot}}(< r) = -\frac{kT r}{\mu m_p G} \left( \frac{d \ln \rho_{\text{gas}}}{d \ln r} + \frac{d \ln T}{d \ln r} \right) \]
Cyg A is similar to High $z$ Radio Galaxy

FR II / FR I Transition

$L_r = 10^{45}$ erg/s
$L_J = 10^{46}$ erg/s

Cyg A

3C295
3 Phase-Evolution of Jets

3C295

3C132

3C341
Weak shock

Hot Cluster Gas

Density Profile

Beam & Hot Spot: Particle Acceleration

Cluster Gas

Bow Shock

Weak shock

Shocked Cluster Gas

--- 100 kpc ---
The Present State of Cygnus A

- Cygnus A is in a cluster: \( M(R < 500 \text{ kpc}) = 2 \times 10^{14} \text{ M}_\odot \) (Smith et al. 2002);
- Gas density profile is shallower than given by ROSAT observations: \( n_{\text{Gas}} \sim r^{-1.4} \)
- The synchrotron-age of Cyg A (27 Myr) is compatible with the Sedov-phase:
- \( \rightarrow \) if the density profile was as flat as measured by Chandra;
- \( \rightarrow \) core density is about \( 0.1 \text{ cm}^{-3} \), \( L_{\text{Jet}} = 1 \times 10^{46} \text{ erg/s} \);
- \( \rightarrow \) the eastern Jet is just on the way to break out.
- \( \rightarrow \) Cocoon cylindrical: due to magnetic confinement ? or due to low Mach numbers ?
Large-Scale Simulations on Supercomputers (NEC, HLRS)

Very light Bipolar Jets: NEC SX-5 for 1 month
\[ \rightarrow \text{NEC SX-6,}\]
\[ \& \text{NEC SX-8}\]

\[ \rightarrow 20 \text{Mio years in real life.}\]

Transition from spherical bubble \[ \rightarrow \text{cigar-shape.}\]

M. Krause, LSW
Cyg A is at the End in the Sedov-Phase
\[ E(t) = L_j \cdot t \]
\[ \rho(r) = \rho_0 \left( \frac{R_c}{r} \right)^\kappa, \quad \kappa = 1.4, \quad R_c = 10 \text{ kpc} \]
\[ R(t) = \left( \frac{(3-\kappa)(5-\kappa)}{12 \pi \rho_0 R_c^{\kappa}} \right)^{\frac{1}{5-\kappa}} \cdot t^{\frac{3}{5-\kappa}} \]
\[ R(t) = 3.3 \text{ kpc} \left( \frac{t}{\text{Myr}} \right)^{1.2} \]
\[ t = 27 \text{ Myr} \rightarrow R = 51 \text{ kpc} \]
Density Contrast Cyg A: \( \eta = \frac{\rho_j h_j \Gamma^2}{\rho_0} \)

\[ L_{\text{kin}} = \pi R_j^2 \Gamma (h_j \Gamma - 1) \rho_j \beta c^3 \]

\[ \frac{L_{\text{kin}}}{\pi R_j^2 \rho_0 \eta c^3} = \beta (1 - \frac{1}{h_j \Gamma}) = \chi < 1 \]

\[ \eta = \frac{0.0002}{\chi} \frac{L_{\text{kin}}}{10^{46} \text{ erg/s}} \frac{0.1 \text{ cm}^{-3}}{n_0} \left( \frac{0.55 \text{ kpc}}{R_j} \right)^2 \]
Consistency Check for Cyg A

\[ \dot{M}_j = \pi R_j^2 \eta \rho_0 \frac{c \beta}{\Gamma h_j} = 0.35 \, M_\odot \, \text{yr}^{-1} \frac{\eta_{-3} \beta}{\Gamma h_j} \left( \frac{2R_j}{\text{kpc}} \right)^2 \]

\[ L_{\text{kin}} = \dot{M}_j c^2 h_j \Gamma \chi / \beta \]

\[ L_{\text{kin}} = 2 \times 10^{46} \, \text{erg/s} \, \eta_{-3} \chi \frac{n_0}{0.1 \, \text{cm}^{-3}} \left( \frac{2R_j}{\text{kpc}} \right)^2 \]

\[ \chi = \beta \left(1 - \frac{1}{h_j \Gamma} \right) = \frac{1}{3} \]
Morphology similar KH instabilities suppressed contact discontinuity in head region is more stable. Cocoon still not cylindrical M. Krause 2004
What happens at $z > 2$?

- Background density is higher and ambient temperature lower (virial temperature):
  - $\eta$ is even smaller, $\eta = 0.0001$;
  - Sedov phase lasts longer, Jet extension therefore smaller;
  - Cooling becomes important;
  - Shocked cluster gas cools by Ly alpha emission;
- Structure of the Jet changes;
- Mixing is very efficient.
Density: after 1.4 – 3.0 – 6.8 Mio years
Background: n = 10 / cm³

Cooling leads to Fragmentation of Bow Shock

M. Krause, LSW
Temperature Diagnostics

$T_n, t = 6.758 \text{ Ma}$
What we have achieved

• We extended Jet simulations to $\eta \ll 0.01$!
• Parameters for Cyg A are now fixed
  ➔ Cyg A is at the end of the Sedov phase;
• Original cluster density profile is crucial;
• At higher redshifts, higher central densities,
  $n_0 > 1 / \text{cm}^3$, ➔ cooling important
  ➔ Ly alpha emission and absorption;
• ➔ mixing of shocked cluster gas with cocoon
  ➔ fingers of cold gas in the cocoon near center;
  ➔ star formation with Jeans mass of 1 Mio solar masses ➔ globular clusters (Krause 2002)?
Critical Issues

• Magnetic fields have to be included in beam and cocoon → magnetosonic Mach number = 3;
• Beam plasma is always hot – very hot, stays hot → $T_{\text{Beam}} > 10^{11}$ K, $M = 3 - 6$ fixed, not free!
• → Beam/cocoon plasma is a 2-component plasma:
  → ions are thermal and non-relativistic
  → electrons relativistic and bumpy (3C 273 knots)!
• → requires completely new code development in the future: relativistic 2-component MHD codes!
• Understanding of internal knots in Beams (M 87, 3C 273, ...) is in the far future!