Three dimensional modeling of FR-II jets using two-temperature MHD simulation

Ohmura Takumi, Machida Mami (Kyushu Univ.)

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1. Introduction - FR II Radio Galaxies -

Most of FR II sources have powerful jets
- Edge brightened sources (hotspot, Radio-lobe)
  Synchrotron radiation from relativistic electrons in the magnetic fields of lobes.
- Diffuse thermal X-ray emitted like a rugby ball.

Blue: X-ray, Red: Radio
1. Introduction - FR II Radio Galaxies -

Classical theory of FR II jets (e.g., Scheuer 1974)

- Jets convert kinetic energy into particles and internal energy at the terminal shocks = Hotspots
- The hot plasma through the hotspots back towards to the nucleus, spreading out = Radio-lobe (Cocoon)
- The layer of shocked plasma emitted diffuse X-ray.
1. Introduction - Two-temperature plasma - X-ray cavity in the galaxy cluster

- Jet plasma is hotter and lighter than ICM

\[
\left[ n_{\text{ICM}} \sim 10^{-2} - 10^{-3} \text{ cm}^{-3}, T_{\text{ICM}} \sim 10^7 - 10^8 \text{K} \right]
\]

- Relaxation time scale of electrons and ions through Coulomb coupling is longer than the propagation time scale.

\[
\tau_{\text{ei}} \geq \tau_{\text{dyn}} \quad \tau_{\text{ei}} \propto n^{-1} T_e^{3/2}
\]

- Electrons and ions could be decoupled in jets.

\[ p_{\text{electron}} \neq p_{\text{ion}} \]
1. Introduction - Energetics of radio-lobe -

- Pressure balance of radio-lobe, $P_{\text{ext}} \leq P_{\text{ion}} + P_{\text{ele}}$
- The under-pressured lobe indicate the existence of the non-radiating ions in the FR-II jets.

$P_{\text{ext}} + P_{\text{ram}}$

(Belsole+ 2007)
1. Introduction - Energetics of radio-lobe -

- Pressure balance of radio-lobe, $P_{\text{ext}} \leq P_{\text{ion}} + P_{\text{ele}}$

- The under-pressured lobe indicate the existence of the non-radiating ions in the FR-II jets.

- We can only estimate electron energy through radiation.

- The ion energy are undetectable with current observational techniques!!
1. Introduction - Motivations -

We investigate

- the spatial energy distribution of electron and ion through two-temperature MHD jets simulation.

- the pressure balance between jet and surrounding medium, especially possibility of electron under-pressured lobe.
Method
- Basic equations
- The fraction of electron heating
- Model
2. Method - Basic equations -

Assumption

- Electron-Ion plasma, \( n = n_i = n_e \)
- One fluid approximation
- Electron and Ion have distinct temperature

MHD Eqs. + Electron and Ion. energy Eqs.

\[
\begin{align*}
nT_i \frac{ds_i}{dt} &= -q^{ie} + (1 - f_e)q^{heat} \\
nT_e \frac{ds_e}{dt} &= +q^{ie} + f_e q^{heat} - q^{rad}
\end{align*}
\]

[Colulomb]  [Dissipation]  [Radiation]
2. Method - The fraction of electron heating -

Model 1: Turbulent dissipation into the electron and ions.
\[ f_e = f_e(T_e/T_i, \beta_i) \]
Magnetic energy dominant region: \( f_e \rightarrow 1 \) (electron heating),
Thermal energy dominant region: \( f_e \rightarrow 0 \) (ion heating)

Model 2: Dissipation in collisionless shock.
\[ f_e = 0.05 \]
Shocks heat ions (e.g., Ghavamian+2013, Matsukiyo+2010).

\[ 0 < f_e < 1 \]
\[ u_{\text{dis}} \rightarrow f_e u_{\text{ele.}} \rightarrow 1 - f_e u_{\text{ion}} \]
2. Method - Model -

MHD CODE : CANS+ (Matsumoto+2019, Ohmura+ 2019)

Uniform Grids: (800,800,1200)

Jets parameter

\[ L_{\text{kin}} = 2.0 \times 10^{46} \text{erg/s} \]
\[ T_e = T_i = 3.0 \times 10^9 \text{K} \]

Initial ICM profile

\[ \beta\text{-profile} \ (\text{King} + 1972) \]
\[ \rho(r) = \rho_0 \left\{1 + \left(\frac{r}{r_c}\right)^2\right\}^{-3\beta/2} \]
\[ T_e = T_i = 2.3 \times 10^7 \text{K} \ (2\text{KeV}) \]
\[ \rho_0 = 8.35 \times 10^{-26} \text{g/cc}, \ r_c = 30\text{kpc}, \ \beta = 1/2 \]
Results

- Overview
- Energetics in jets
- Under-pressured lobe
3. Results - Overview -
- Beam can reach termination, and form the terminal shocked.
- The most of heating energy goes to ions.
3. Results - Energetics in jets -
Volume-weighted pressure in radio-lobe.

\[ P_{i,e,B}(z) = \frac{\int p_i,e,B \, 2\pi r \, dr \, dz}{\int 2\pi r \, dr \, dz} \quad p_B = B^2 / 8\pi \]
3. Results - Energetics in jets -

- In shocked-ICM, Ions and electrons decouple by bowshock. But, Coulomb interaction is effective because density is high.
- The lobe electron pressure is lower than shocked-ICM.
3. Results - Energetics in jets -

- Shocked-ICM electron pressure is higher than surrounding electron pressure everywhere.
- Lobe electrons have lower energy than ICM electrons ($z<80$).
3. Results - Under-pressured lobe -

- Shocked-ICM electron pressure is higher than surrounding electron pressure everywhere.
- On the other hand, lobe electron pressure is low.
Discussion
4. Discussion - Under-pressured lobe -
- The bow (cocoon) shocks of Cyg.A are clearly seen in high-resolution Chandra observations.
- Shock compression is clearly observed at these shocks.

0.5-7.0 KeV X-ray (Chandra), *contour 4.5 GHz (VLA)*

(de Vries+ 2019, Snios+2018)
4. Discussion - Under-pressured lobe -
- However, the pressure of the eastern lobe, which is estimated by X-ray Inverse Compton, is lower than the rim pressure, i.e., **Under-pressured lobe**.

- These observational analysis indicates that

\[ P_{\text{lobe}} < P_{\text{ICM}} < P_{\text{shocked-ICM}} \]

<table>
<thead>
<tr>
<th></th>
<th>( P_{\text{rim}}^a ) ((10^{-10} \text{ erg cm}^{-3}))</th>
<th>( \gamma_{\text{min}}^b )</th>
<th>( P_{\text{IC}}^c ) ((10^{-10} \text{ erg cm}^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>East</td>
<td>(10.4 \pm 0.4)</td>
<td>1</td>
<td>(5.8^{+2.0}_{-1.4})</td>
</tr>
<tr>
<td></td>
<td>(10)</td>
<td>(2.2^{+0.4}_{-0.4})</td>
<td></td>
</tr>
<tr>
<td>West</td>
<td>(8.4 \pm 0.2)</td>
<td>1</td>
<td>(140^{+1690}_{-116})</td>
</tr>
<tr>
<td></td>
<td>(10)</td>
<td>(18^{+40}_{-10})</td>
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</tbody>
</table>

\(^a\): \(^b\): \(^c\): (de Vries+ 2019)
4. Discussion - Under-pressured lobe -

However, the pressure of the eastern lobe, which is estimated by X-ray Inverse Compton, is lower than the rim pressure, i.e., $P_{\text{lobe}} < P_{\text{ICM}} < P_{\text{shocked-ICM}}$.

Our two-temperature jets model could explain this pressure condition.

The observational results indicate that these observational results indicate that our two-temperature jets model could explain this pressure condition.

$P_{\text{lobe}} < P_{\text{ICM}} < P_{\text{shocked-ICM}}$
5. Summary

- We have carried out high-resolution two-temperature MHD jets propagate simulations.

- Beam, which propagating up to 100 kpc, can reach termination of jets, and terminal shock (hotspot) is formed.

- The magnetic energy is much less than the ion thermal energy, and hence most of heating energy goes to ions.

- The lobe electron pressure is lower than that of shocked-ICM and surrounding ICM, and under-pressured lobe is formed.