An Inhomogeneous Jet Model for the Broad-Band Emission of Radio Loud AGNs

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Motivations

Numerical modeling

Compton rocket

Two-flow paradigm

Application to 3C273
Motivations: open issues & 1-zone model

- Jet composition ($p^+ \text{ vs } e^-$)
- Jet power (Celotti & Ghisellini ++)
- Discrepancies in $\Gamma_b$ (Bulk Lorentz Factor Crisis, Henri & Saugé 06)
- Acceleration and confinement of highly relativistic flows
- Location of emitting zone (Aharonian et al 09, Barres de Almeida 10)
- Uncorrelated variability (Aharonian et al 09, Aleksic et al 15)
Motivations: open issues & 1-zone model

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- Jet power (Celotti $\&$ Ghisellini $++)$
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  ($Bulk$ Lorentz Factor Crisis, Henri $\&$ Saugé $06$)
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  (Aharonian et al $09$, Barres de Almeida $10$)
- Uncorrelated variability
  (Aharonian et al $09$, Aleksic et al $15$)

$\Rightarrow$ 1-zone is physically limited and unsatisfactory

$\Rightarrow$ Need more complex models
Motivations: structured jets models

- Spine/sheath (Ghisellini et al. 05)
Motivations: structured jets models

- **Spine/sheath** (Ghisellini et al. 05)
- **Blob-in-jet** (Katarzynski 01, Hervert et al. 15)
Motivations: structured jets models

- **Spine/sheath** (Ghisellini et al. 2005)
- **Blob-in-jet** (Katarzynski 2001, Hervet et al. 2015)
- **Two-flow** (Sol et al. 1989, Henri & Pelletier 1991)
Motivations: structured jets models

- **Spine/sheath** (Ghisellini et al. 05)  
  ![Spine/sheath diagram](image)
  - Introduce more physics
  - Can potentially solve the current issues
  - Pushed by observations

- **Blob-in-jet** (Katarzynski 01, Hervet et al. 15)  
  ![Blob-in-jet diagram](image)

- **Two-flow** (Sol et al. 89, Henri & Pelletier 91)  
  ![Two-flow diagram](image)
Motivations: structured jets

$\Gamma \approx 2.5$

$\Gamma \approx 6$

M87, Mertens et al. 15

3C 84, Nagai et al. 14
Motivations

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Application to 3C273
The Two-Flow: hypothesis

*H. Sol, G. Pelletier, E. Asséo, 1989
The Two-Flow: hypothesis

MHD jet or wind
- Fuelled by accretion disk
- Baryon loaded
- Midly relativistic ($\approx 0.5c$)
- Carries most of the power

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**Inner Jet**
- Pairs $e^-/e^+$ (NO baryons here)
- Highly relativistic ($\Gamma \approx 10$)
- Responsible for most of the non-thermal emission
- Modeled

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The Two-Flow hypothesis

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- Pairs get energy through the two flows interaction ($2^{nd}$ order Fermi process)

*H. Sol, G. Pelletier, E. Asséo, 1989*
The Two-Flow: hypothesis

Turbulence + Pairs

2\textsuperscript{nd} order
Fermi
High-energy pairs
Inverse Compton
\(\gamma\)-rays
\(\gamma-\gamma\)
absorption

New Pairs
The Two-Flow: hypothesis

- Turbulence + Pairs
  - Quickly get a lot of pairs!
  - Jet loading
  - 2nd order
  - Fermi
  - High-energy pairs
  - Inverse Compton
  - γ-rays
  - γ-γ absorption

New Pairs

Quickly get a lot of pairs!

Jet loading

2nd order

Fermi

High-energy pairs

Inverse Compton

γ-rays

γ-γ absorption
The Two-Flow hypothesis

Turbulence + Pairs

Quickly get a lot of pairs!

2\textsuperscript{nd} order Fermi

High-energy pairs

Inverse Compton

Jet loading Flares

\(\gamma\)-rays

\(\gamma\)-\(\gamma\) absorption
The Two-Flow : interest

- Speeds discrepancy in jets

\[ \Gamma \approx 2 \]

\[ \Gamma \approx 10 \]
The Two-Flow: interest

Speeds discrepancy in jets

$\Gamma \approx 2$

$\Gamma \approx 10$

Bulk acceleration via Compton rocket
The Two-Flow: interest

- Speeds discrepancy in jets
  - $\Gamma \approx 10$
  - $\Gamma \approx 2$

- Bulk acceleration via Compton rocket
- Highly relativistic flow confinement
The Two-Flow: interest

- Bulk acceleration via Compton rocket
- Coherent and comprehensive picture of AGN jets
- Highly relativistic flow confinement
- Speeds discrepancy in jets

\[ \Gamma \approx 2 \]
\[ \Gamma \approx 10 \]
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Application to 3C273
Modeling the jet

Standard accretion disc
Modeling the jet

Dusty torus in thermal equilibrium
Modeling the jet

Broad Line Region (absorb & re-emits disc radiation)
Modeling the jet

Jet slices
(adaptative size)
- $R(z) = \text{jet radius}$
- $B(z) = \text{magnetic field}$
- $Q(z) = \text{heating term}$
Modeling the jet

Particle distribution:
- $n(\gamma, z)$
Modeling the jet

Emission processes:
• Synchrotron
Modeling the jet

Emission processes:
• Synchrotron
• Synchrotron self-Compton
Modeling the jet

Emission processes:
• Synchrotron
• Synchrotron self-Compton
• External Compton
Modeling the jet

Absorption & pair-creation
Modeling the jet

Bulk Lorentz factor + observation angle
Modeling the jet – particle distribution

Pile-up:

\[ n_e(\gamma, Z) = N_e(Z) \frac{\gamma^2}{2\bar{\gamma}^3(Z)} \exp \left( -\frac{\gamma}{\bar{\gamma}(Z)} \right) \]

Result from stochastic acceleration processes
Modeling the jet – particle distribution

Pile-up:

\[
n_e(\gamma, Z) = N_e(Z) \frac{\gamma^2}{2\bar{\gamma}^3(Z)} \exp \left(-\frac{\gamma}{\bar{\gamma}(Z)}\right)
\]

Result from stochastic acceleration processes

Result from pair-production & annihilation
Modeling the jet – particle distribution

**Pile-up:**

\[ n_e(\gamma, Z) = N_e(Z) \frac{\gamma^2}{2\bar{\gamma}^3(Z)} \exp \left( -\frac{\gamma}{\bar{\gamma}(Z)} \right) \]

Result from stochastic acceleration processes

Result from pair-production & annihilation

Balance between cooling (emission) and heating (Q(z))
Modeling the jet – particle distribution

Pile-up:

\[ n_e(\gamma, Z) = N_e(Z) \frac{\gamma^2}{2\bar{\gamma}^3(Z)} \exp \left( -\frac{\gamma}{\bar{\gamma}(Z)} \right) \]

Result from stochastic acceleration processes

Result from pair-production & annihilation

Balance between cooling (emission) and heating (Q(z))

Computed parameters!
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Application to 3C273
The Compton Rocket: principle

- External photon
The Compton Rocket: principle

- External photon
- Inverse Compton photon
The Compton Rocket: principle

*O’Dell (81)
The Compton Rocket: principle

Energy source = MHD turbulence via particles
NOT external photon field

Cooling compensated by continuous re-acceleration
(≠ Phinney 82)

*O’Dell (81)
The Compton Rocket : equilibrium

- $\Gamma(z) = \Gamma_{eq}(z)$ in the inner parts of the jet
  - Implied by the spatial distribution of the external photon field
  - Does not depend on particles energetics (in Thomson regime)

- $\Gamma(z) \rightarrow \Gamma_\infty$
  - Implied by particles energetics

$\Gamma(z)$ not a free parameter

*Vuillaume et al 15*
Modeling the jet

3 power-laws \((R(z), B(z), Q(z))\)  
+ initial conditions at the base of the jet  
+ external sources

=> Compute self-coherent:  
- \(n(\gamma,z)\)  
- \(\Gamma(z)\) (Compton rocket)  
- Particles emission  
  (synchrotron, ssc, ec)  
- Pair production  
- Absorption  
- Anisotropy of the sources and emission
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Application to 3C273
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Data from Turler et al (1999)
Application to 3C 273

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Standard Accretion disc
Dusty torus
Broad Line Region (not visible here)
Application to 3C 273

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Dusty torus
Broad Line Region (not visible here)
Synchrotron
Synchrotron self-Compton
External Compton
Application to 3C 273

Different jet altitude = different part of the spectrum

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- Dusty torus
- Broad Line Region (not visible here)
- Synchrotron
- Synchrotron self-Compton
- External Compton
Different jet altitude = different part of the spectrum

Data from Turler et al (1999)

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Hot corona power-law added
(Haardt et al 98)
Conclusion

- AGN jets modelling in the two-flow paradigm
- Complex and coherent model
- Physical conditions
  - Imposed by observations
  - Computed along the jet from initial conditions at the base
- Model able to reproduce the broad-band emission of 3C273
Back-up slides
The Compton Rocket: equilibrium

- External photon
- Inverse Compton photon

Compton Rocket
The Compton Rocket: equilibrium

- External photon
- Inverse Compton photon

Compton Rocket

Compton Drag
The Compton Rocket: equilibrium

- External photon
- Inverse Compton photon

\[ \Gamma < \Gamma_{eq} \]
\[ \Gamma = \Gamma_{eq} \]
\[ \Gamma > \Gamma_{eq} \]
The Compton Rocket: equilibrium

Instant equilibrium for hot pairs!

\[ t_{IC}(\gamma_e) \ll t_{dyn} = \frac{Z}{c} \]

⇒ Compton rocket imposes \( \Gamma = \Gamma_{eq} \)

(as long as \( t_{IC}(\gamma_e) \ll t_{dyn} \))
Compton rocket with a standard accretion disc

*Vuillaume et al (2015)*
Compton rocket with a standard accretion disc

\[ t_t(\gamma_e, Z) \approx Z/c \]

Jet prescription

\[ R(Z) = R_0 \left( \frac{Z}{Z_0} + \left( \frac{R_i}{R_0} \right)^{1/\omega} \right)^\omega \]

\[ Q(Z) = Q_0 \left( \frac{Z}{Z_0} + \left( \frac{R_i}{R_0} \right)^{1/\omega} \right)^{-\zeta} \exp \left( -\frac{Z}{Z_c} \right) \]

\[ B(Z) = B_0 \left( \frac{R(Z)}{R_0} \right)^{-\lambda} \]
Sources modeling

Sources are described geometrically and “sliced” for numerical integration.
III. Resulting $\Gamma_{eq}$ in AGN photon field

Finite accretion disc  
+ dusty torus  
+ BLR

$R_{out} = 10^4 R_S$  
$R_{blr} = 10^3 R_S$  
$R_t = 4 \cdot 10^4 R_S$

*Vuillaume et al (2015)*