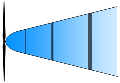
ExHaLe-jet: an Extended Hadro-Leptonic jet model for blazars

Michael Zacharias,
Anita Reimer, Catherine Boisson, Andreas Zech

LUTH, Observatoire de Paris, Meudon, France
Centre for Space Research, North-West University Potchefstroom, South Africa



HEASA 2021
Sep 13-17, 2021

Introduction

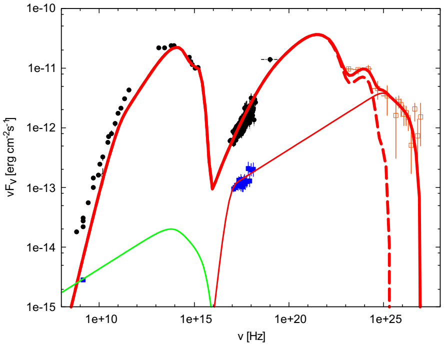


Figure 1: Model: one-zone core (dashed red), kpc-scale jet (thin solid), total (thick solid), MZ&Wagner16

- Blazars are well described through the one-zone model
- Noteworthy counter-examples are:
  - AP Librae Hervet+15, Sanchez+16, MZ&Wagner16
  - Centaurus A HESS+20
- Need for extended, kinetic jet models

Potter&Cotter12,13, Zdziarski+14, Lucchini+19, . . .

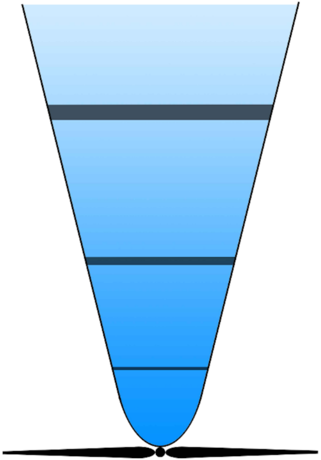


Figure 2: Sketch: jet cut into numerous slices (dark), in which the kinetic equations for each particle species are solved Figure: courtesy of Jonathan Heil

An **Ex**tended **Ha**dro-**Le**ptonic jet model

- Jet length cut into numerous slices, where the Fokker-Planck equation is solved for all species
  - Injection of primary proton and electron distribution at the base; evolved self-consistently along the jet
  - Injection of secondaries (pions, muons, pairs) in each slice
  - Pairs propagated along with primaries
  - Radiation and neutrino output for each slice

$$\frac{\partial n_i(\chi,t)}{\partial t} = \frac{\partial}{\partial \chi}\left[\frac{\chi^2}{(a+2)t_{\mathrm{acc}}}\frac{\partial n_i(\chi,t)}{\partial \chi}\right] - \frac{\partial}{\partial \chi}\left(\dot{\chi}_i n_i(\chi,t)\right) + Q_i(\chi,t) - \frac{n_i(\chi,t)}{t_{\mathrm{esc}}} - \frac{n_i(\chi,t)}{\gamma t^*_{i,\mathrm{decay}}}$$

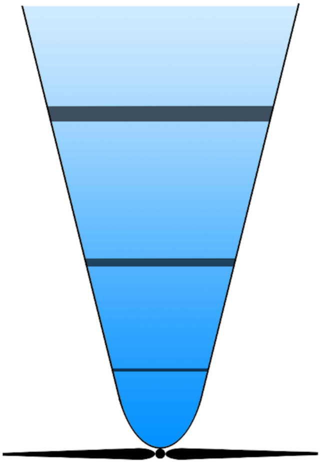


Figure 3: Sketch: jet cut into numerous slices (dark), in which the kinetic equations for each particle species are solved Figure: courtesy of Jonathan Heil

An **Ex**tended **Ha**dro-**Le**ptonic jet model

- Geometry currently fixed as
  - Parabolic acceleration region: $\Gamma_b(z) \propto \sqrt{z}$
  - Conical coasting region $\Gamma_b(z) =$const.
  - Radius: $R(z) \propto \tan\left[0.26/\Gamma_b(z)\right]$
  - Magnetic field derived self-consistently
- Considering internal and external radiation fields
  - Synchrotron, π^0, Inverse-Compton
  - Accretion Disk, BLR, DT, CMB
  - BLR and DT (luminosity and size) depend on Accretion Disk

ExHaLe-jet: First results

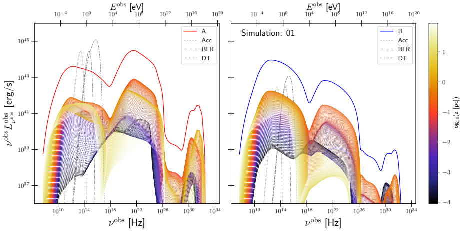


Figure 4: Total spectrum (observer's frame) with distance evolution (color code) for strong (left) and weak (right) accretion disk.

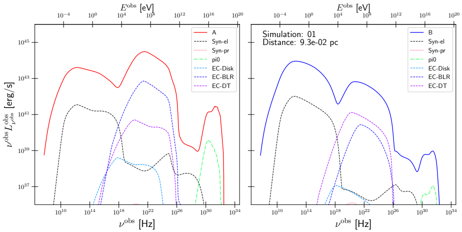


Figure 5: Total spectrum (observer's frame) showing individual contributions at a distance of $\sim$ 0.1pc

- Length scales:
  - $z_{max} = 100$pc, $z_{acc} = 1$pc
  - $R_{BLR} \sim 0.05$pc (strong), ~ 0.005pc (weak)
  - $R_{DT} \sim 1$pc (strong), ~ 0.1pc (weak)
- Photon spectrum dominated by leptonic processes (synchrotron, external Compton)
- Strongest contribution around 0.1–1 z_{acc}
- External fields have strong impact (*left*: strong disk, *right*: weak disk)
  - "Compton dominance"
  - p-γ interactions (cf. π^0 bump)

ExHaLe-jet: First results

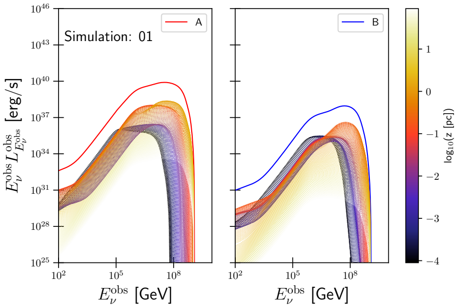


Figure 6: Total neutrino spectrum (observer's frame) with distance evolution (color code) for a strong (left) and weak (right) accretion disk.

- Length scales:
  - $z_{max} = 100$pc, $z_{acc} = 1$pc
  - $R_{BLR} \sim 0.05$pc (strong), ~ 0.005pc (weak)
  - $R_{DT} \sim 1$pc (strong), ~ 0.1pc (weak)
- Photon spectrum dominated by leptonic processes (synchrotron, external Compton)
- Strongest contribution around 0.1–1 z_{acc}
- External fields have strong impact (*left*: strong disk, *right*: weak disk)
  - "Compton dominance"
  - p-γ interactions (cf. π^0 bump)
  - Neutrino spectra
- Total jet power sub-Eddington
- Jet power dominated by magnetic field (initial value $B(0) = 200$G)

ExHaLe-jet: First results

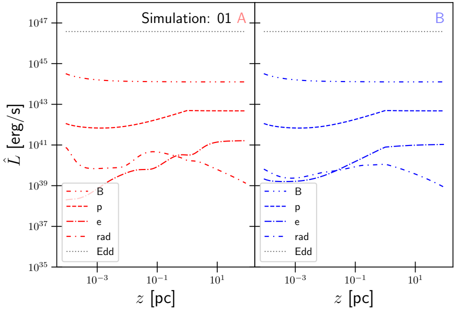


Figure 6: Luminosities (host galaxy frame) over distance for a strong (left) and weak (right) accretion disk.

- Length scales:
  - $z_{max} = 100$pc, $z_{acc} = 1$pc
  - $R_{BLR} \sim 0.05$pc (strong), ~ 0.005pc (weak)
  - $R_{DT} \sim 1$pc (strong), ~ 0.1pc (weak)
- Photon spectrum dominated by leptonic processes (synchrotron, external Compton)
- Strongest contribution around 0.1–1 z_{acc}
- External fields have strong impact (*left*: strong disk, *right*: weak disk)
  - “Compton dominance”
  - p-γ interactions (cf. π^0 bump)
  - Neutrino spectra
- Total jet power sub-Eddington
- Jet power dominated by magnetic field (initial value $B(0) = 200$G)

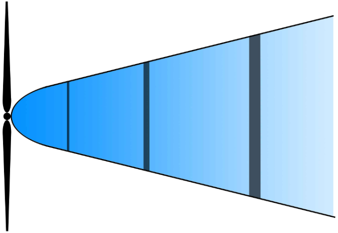


Figure 7: Sketch: jet cut into numerous slices (dark), in which the kinetic equations for each particle species are solved Figure: courtesy of Jonathan Heil

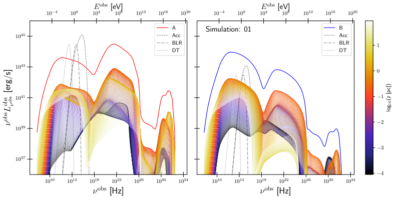


Figure 8: Total spectrum (observer's frame) with distance evolution (color code) for strong (left) and weak (right) accretion disk.

An **Ex**tended **Ha**dro-**Le**ptonic jet model

- Flexible, kinetic, hadro-leptonic code to model the emission from an extended jet
- Parameter set results in a leptonic dominance in the spectrum
- Influence of protons (secondaries, neutrinos, etc) important

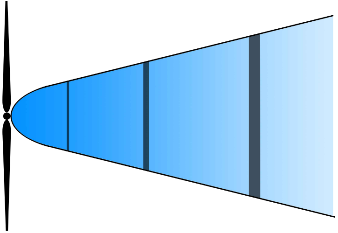


Figure 7: Sketch: jet cut into numerous slices (dark), in which the kinetic equations for each particle species are solved Figure: courtesy of Jonathan Heil

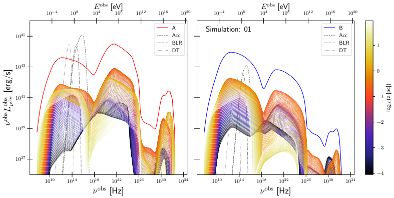


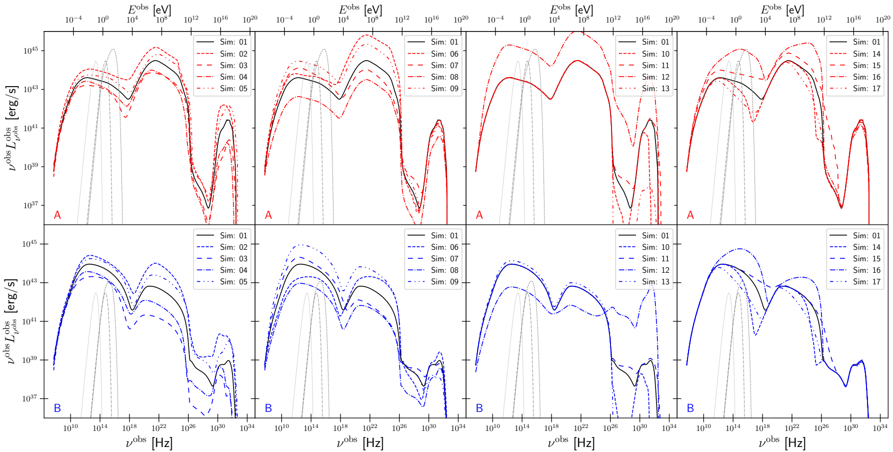
Figure 8: Total spectrum (observer's frame) with distance evolution (color code) for strong (left) and weak (right) accretion disk.

An **Ex**tended **Ha**dro-**Le**ptonic jet model

- Flexible, kinetic, hadro-leptonic code to model the emission from an extended jet
- Parameter set results in a leptonic dominance in the spectrum
- Influence of protons (secondaries, neutrinos, etc) important

Thank you!

BACKUP



- 1st: Length of acceleration region (02, 03), Doppler boosting (04, 05)
- 2nd: Magnetic field (06, 07), injection power (08), proton-to-electron ratio (09)
- 3rd: Proton maximum Lorentz factor (10, 11), Proton spectral index (12, 13)
- 4th: Electron maximum Lorentz factor (14, 15), Electron spectral index (16, 17)

Processes considered in the code

Cooling processes:

- Protons: synchrotron, adiabatic, p-γ, Bethe-Heitler
- Charged pions / muons: synchrotron, adiabatic
- Electrons: synchrotron, adiabatic, inverse Compton

Acceleration processes:

- Fermi I/II, but only as a “re-acceleration”
- Main acceleration through a generic injection term

Photon absorption processes:

- Pair production on all photon fields (external ones angle averaged in the comoving frame after boosting)
- Synchrotron-self absorption
- Photons that left the emission region, are also absorbed in the BLR and DT fields (but no EBL or CMB absorption considered)

Table 1: Parameters and values of the simulation

Parameter	Value	Parameter	Value
Redshift	0.5		
Black hole mass	$3.0 \times 10^8\, M_\odot$	Initial magnetic field	100 G
Eddington ratio	A: 10^{-1}	Frac injected proton luminosity	0.1
	B: 10^{-3}	Initial proton to electron ratio	1
BLR temperature	10^4 K	Minimum proton Lorentz factor	2
DT temperature	5.0×10^2 K	Maximum proton Lorentz factor	2×10^8
Jet length	100 pc	Proton spectral index	2.5
Acceleration region	1 pc	Minimum electron Lorentz factor	100
Max jet Lorentz factor	30.0	Maximum electron Lorentz factor	1×10^5
Jet viewing angle	1.9°	Electron spectral index	2.5
Frac Jet opening angle	0.26		
Frac Initial jet width	10.0		
Frac Escape time scale	10.0		
Frac Acceleration time scale	10.0		