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# RAiSE HD: Lagrangian particle-based radio AGN model

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This document describes the functions in the RAiSE HD code and provides examples of accepted usage to simulate relativistic jets from radio Active Galactic Nuclei and plot emissivity maps throughout source history. The code is written in *python* and imports standard packages including `numpy`, `scipy` and `matplotlib`.

Radio AGN in Semi-Analytic Environments (RAiSE) model for the expansion and evolution of the jets and lobes emanating from extraglactic supermassive black holes. The RAiSE HD (hydrodynamics) version of this model adapts Lagrangian particles from a hydrodynamical simulation to the dynamics from the analytical theory, yielding a physically-based magnetic field structure on both large and local scales. This code release enables the user to generate radio-frequency and X-ray wavelength surface brigtness images of Fanaroff-Riley Type-II radio AGNs across their evolutionary history, including for the jet, active lobe and remnant lobe. Parallised code can be run to generate a catalogue of mock radio AGNs to, for example: run parameter inversions to measure the energetics of observed objects; or produce high-resolution animations for data visualisations. The code is written in Python 2/3 and has detailed documentation and worked examples available on GitHub (https://github.com/rossjturner/RAiSEHD).

## INSTALLATION

This package can either be installed using *pip* or from a .zip file downloaded from the GitHub repository using the standard Python distutils.

### Install using pip

The following command will install the latest version of the *RAiSE* library from the Python Packaging Index (PyPI):

```
>>> pip install RAiSE
```

### Install from GitHub repository

The package can be downloaded from the GitHub repository at `https://github.com/rossjturner/RAiSEHD`, or cloned with *git* using:

```
>>> git clone https://github.com/rossjturner/RAiSEHD.git
```

The package is installed by running the following command as an administrative user:

```
>>> python setup.py install
```

## CONTACT DETAILS

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## PUBLIC FUNCTIONS

### RAiSE_run

RAiSE.RAiSE_run(frequency, redshift, axis_ratio, jet_power, source_age, halo_mass=None, rand_profile=False, betas=None, regions=None, rho0Value=None, active_age=10.14, jet_lorentz=5, equipartition=-1.5, spectral_index=0.7, gammaCValue=5./3, lorentz_min=780, brightness=True, resolution='standard', seed=None, aj_star=0.2305, fill_factor=0.1545, jet_angle=0.5375)

Function to define main variables in RAiSE HD, test input variables and convert when necessary. All further functions documented will call upon this definition when testing inputs.

**Parameters:**

**frequency :** ***float, list or numpy array***
Specify (one or more) frequencies for the synchrotron/inverse Compton radiation from the lobe. Synchrotron radiation is simulated for frequencies $\log_{10} f < 12$, otherwise inverse-Compton emission is modelled. Expected units of log Hertz.

**redshift :** ***float, list or numpy array***
Specify (one or more) redshifts for the AGN lobes.

**axis_ratio :** ***float, list or numpy array***
Specify (one or more) late-time axis ratios for the lobes of the Fanaroff-Riley type-II type morphology. In this work, the axis ratio is defined as the ratio of the jet length and maximum radius along the minor axis.

**jet_power :** ***float, list or numpy array***
Specify (one or more) jet powers for total power of both jets propelled from central black hole. Expected units are log Watts.

**source_age :** ***float, list or numpy array***
Specify (one or more) ages for the AGN lobes. Expected units are log years.

**halo_mass :** ***float, list or numpy array, optional***
Specify (one or more) halo masses of environment surrounding the AGN lobes. Expected units of log solar masses. This parameter is not required if a user-defined gas density profile is specified using `betas`, `regions`, `rho0Value` and `temperature`.

**rand_profile:** ***boolean, optional***
Specify whether to include pseudo-random perturbations to the gas density profiles based on the observed cluster profiles of Vikhlinin et al. (2006). Random profiles are generated if `rand_profile=True`, otherwise the mean profile shape is assumed. By default the mean cluster profile from Vikhlinin et al. (2006) is assumed, scaled to the user-specifed halo mass.

**betas :** ***string or float, optional***
Specify slope of the power laws approximating the host environment gas density profile. The default value is none.

**regions :** ***string or float, optional***
Specify lower galactocentric radii of the power laws approximating the host environment gas density profile. The lower radius of the first power law must be non-zero; this power law is extended to zero in the code. Expected units are metres. The default is value none.

**rho0Value :** ***string or float, optional***
Specify the gas density at the lower radius of the first power law approximating the host environment gas density profile. Expected units are kilograms per metre cubed. The default value is none.

**temperature :** ***string or float, optional***
Specify temperature of AGN host environment. Expected units in Kelvin. The default value is none.

**active_age :** ***float, optional***
Specify (one or more) active ages for the jets of the central black hole. Expected units are in log years. The default value is 10.14.

**jet_lorentz :** ***float, optional***
Specify Lorentz factor of the bulk flow in plasma in the spine of the AGN jets. Lorentz factor is dimensionless. The default value is 5.

**equipartition:** ***float, optional***
Specify (one or more) equipartition factors; i.e. the ratio of energy in magnetic field to that in the particles. The default value is -1.5.

**spectral_index :** ***float, optional***

Specify value of spectral index, or dependence of radiative flux density on frequency. Spectral index is dimensionless. The default value is 0.7.

**gammaCValue :** ***float, optional***

Specify the adiabatic index of the lobe plasma. The default value is 5.0/3 for a non-relativistic fluid.

**lorentz_min :** ***string, optional***

Specify the minimum Lorentz factor of electron energy distribution at time of shock acceleration.

**brightness :** ***string, optional***

Specify whether to output a surface brightness image of AGN lobe at each frequency. These are output in as .csv file in the LD_tracks file created. The default value is True.

**resolution :** ***string, optional***

Specify resolution, and correspondingly the number of Lagrangian particles, used in surface brightness images. Permitted resolutions are 'best', 'high', 'standard' and 'poor' which correspond to 114 688 000, 28 672 000, 7 168 000 and 1 792 000 particles respectively. The default value is 'standard'.

**seed:** ***string or float, optional***

Specify a seed for the psuedo-random number generator used to produce gas density profiles for the host environment. This parameter is only required if `rand_profile=True`. No seed is provided by default.

**aj_star :** ***float, optional***

Specify the ratio of the radius of the jet spine to sheath. The default value is 0.2305, based on hydrodynamical simulations.

**fill_factor:** ***float, optional***

Specify value for filling factor, the fraction of lobe volume comprising of non-thermal plasma. The default value is 0.1545, based on hydrodynamical simulations.

**jet_angle :** ***float, optional***

Specify the apparent half-opening angle of the jet; this differs from the opening angle of the uncollimated jet referred by other authors in the literature. The expected units are degrees. The default value is 0.5375, based on hydrodynamical simulations.

### RAiSE.RAiSE_evolution_maps

RAiSE.RAiSE_evolution_maps(frequency, redshift, axis_ratio, jet_power, source_age, halo_mass=None, rand_profile=False, betas=None, regions=None, rho0Value=None, temperature=None, active_age=10.14, jet_lorentz = 5, equipartition=-1.5, spectral_index=0.7, gammaCValue=5./3, lorentz_min=Lorentzmin, seed=None, rerun=False, cmap='RdPu' )

Function to plot emissivity maps throughout source evolutionary history. Function can be used to test and observe different types of inputs and alterations to said inputs. Note: For this function to work successfully a halo mass must be chosen, OR, random profile through to temperature must all have values.

**Parameters:**

**frequency :** ***float***

Specify (one or more) frequencies for the synchrotron/inverse Compton radiation from the lobe. Synchrotron radiation is simulated for frequencies $\log_{10} f < 12$, otherwise inverse-Compton emission is modelled. Expected units of log Hertz.

**redshift :** ***float***

Specify (one or more) redshifts for the AGN lobes.

**axis_ratio :** ***float***

Specify (one or more) late-time axis ratios for the lobes of the Fanaroff-Riley type-II type morphology. In this work, the axis ratio is defined as the ratio of the jet length and maximum radius along the minor axis.

**jet_power :** ***float,list or numpy array***

Specify (one or more) jet powers for total power of both jets propelled from central black hole. Expected units are log Watts.

**source_age:** ***float, list or numpy array***

Specify (one or more) ages for the AGN lobes. Expected units are log years.

**halo_mass: *string or float***

Specify (one or more) halo masses of environment surrounding the AGN lobes. Expected units of log solar masses. This parameter is not required if a user-defined gas density profile is specified using `betas`, `regions`, `rho0Value` and `temperature`.

**rand_profile : *boolean, optional***

Specify whether to include pseudo-random perturbations to the gas density profiles based on the observed cluster profiles of Vikhlinin et al. (2006). Random profiles are generated if `rand_profile=True`, otherwise the mean profile shape is assumed. By default the mean cluster profile from Vikhlinin et al. (2006) is assumed, scaled to the user-specifed halo mass.

**betas : *string or float, optional***

Specify slope of the power laws approximating the host environment gas density profile. The default value is none.

**regions : *list or array, optional***

Specify lower galactocentric radii of the power laws approximating the host environment gas density profile. The lower radius of the first power law must be non-zero; this power law is extended to zero in the code. Expected units are metres. The default is value none.

**rho0Value : *string or float, optional***

Specify the gas density at the lower radius of the first power law approximating the host environment gas density profile. Expected units are kilograms per metre cubed. The default value is none.

**temperature: *string or float, optional***

Specify temperature of AGN host environment. Expected units in Kelvin. The default value is none.

**active_age : *float, optional***

Specify (one or more) active ages for the jets of the central black hole. Expected units are in log years. The default value is 10.14.

**jet_lorentz : *float, optional***

Specify Lorentz factor of the bulk flow in plasma in the spine of the AGN jets. Lorentz factor is dimensionless. The default value is 5.

**equipartition : *float, optional***

Specify (one or more) equipartition factors; i.e. the ratio of energy in magnetic field to that in the particles. The default value is -1.5.

**spectral_index : *float, optional***

Specify value of spectral index, or dependence of radiative flux density on frequency. Spectral index is dimensionless. The default value is 0.7.

**gammaCValue : *float, optional***

Specify the adiabatic index of the lobe plasma. The default value is 5.0/3 for a non-relativistic fluid.

**lorentz_min : *string or float, optional***

Specify the minimum Lorentz factor of electron energy distribution at time of shock acceleration.

**seed : *string or float, optional***

Specify a seed for the psuedo-random number generator used to produce gas density profiles for the host environment. This parameter is only required if `rand_profile=True`. No seed is provided by default.

**rerun : *string, optional***

If this line is existent, rerun = ‘True’ will tell RAiSE to rerun the code. The default value is False.

**cmap : *srting, optional***

Specify color of density map plotted. The default value is ’RdPu,’ or red and purple.

**RAiSE.RAiSE_evolution_tracks**

RAiSE.RAiSE_evolution_tracks(frequency, redshift, axis_ratio, jet_power, source_age, halo_mass=None, rand_profile=False, betas=None, regions=None, rho0Value=None, temperature=None, active_age=10.14, jet_lorentz=5., equipartition=-1.5, spectral_index=0.7, gammaCValue=5./3, lorentz_min=Lorentzmin, resolution='standard', seed=None, rerun=False, labels=None, colors=None, linestyles=None

Function to trace various parameters across the radio AGN's evolution. Note: For this function to work successfully, it is required that there is more than one source age; provide a list or array of ages.

**Parameters:**

**frequency :** ***float, list or numpy array***

Specify (one or more) frequencies for the synchrotron/inverse Compton radiation from the lobe. Synchrotron radiation is simulated for frequencies $\log_{10} f < 12$, otherwise inverse-Compton emission is modelled. Expected units of log Hertz.

**redshift:** ***float, list or numpy array***

Specify (one or more) redshifts for the AGN lobes.

**axis_ratio:** ***float, list or numpy array***

Specify (one or more) late-time axis ratios for the lobes of the Fanaroff-Riley type-II type morphology. In this work, the axis ratio is defined as the ratio of the jet length and maximum radius along the minor axis.

**jet_power:** ***float, list or numpy array***

Specify (one or more) jet powers for total power of both jets propelled from central black hole. Expected units are log Watts.

**source_age:** ***list or numpy array***

Specify (one or more) ages for the AGN lobes. Expected units are log years.

**halo_mass:** ***string, float, list or numpy array***

Specify (one or more) halo masses of environment surrounding the AGN lobes. Expected units of log solar masses. This parameter is not required if a user-defined gas density profile is specified using `betas`, `regions`, `rho0Value` and `temperature`.

**rand_profile:** ***boolean, optional***

Specify whether to include pseudo-random perturbations to the gas density profiles based on the observed cluster profiles of Vikhlinin et al. (2006). Random profiles are generated if `rand_profile=True`, otherwise the mean profile shape is assumed. By default the mean cluster profile from Vikhlinin et al. (2006) is assumed, scaled to the user-specifed halo mass.

**betas:** ***list or numpy array, optional***

Specify slope of the power laws approximating the host environment gas density profile. The default value is none.

**regions:** ***list or array, optional***

Specify lower galactocentric radii of the power laws approximating the host environment gas density profile. The lower radius of the first power law must be non-zero; this power law is extended to zero in the code. Expected units are metres. The default is value none.

**rho0Value:** ***string or float, optional***

Specify the gas density at the lower radius of the first power law approximating the host environment gas density profile. Expected units are kilograms per metre cubed. The default value is none.

**temperature:** ***string or float, optional***

Specify temperature of AGN host environment. Expected units in Kelvin. The default value is none.

**active_age:** ***float, optional***

Specify (one or more) active ages for the jets of the central black hole. Expected units are in log years. The default value is 10.14.

**jet_lorentz:** ***float, optional***

Specify Lorentz factor of the bulk flow in plasma in the spine of the AGN jets. Lorentz factor is dimensionless. The default value is 5.

**equipartition:** ***float, optional***

Specify value of spectral index, or dependence of radiative flux density on frequency. Spectral index is dimensionless. The default value is 0.7.

**spectral_index:** ***float, optional***

Specify value of spectral index, or dependence of radiative flux density on frequency. Spectral index is dimensionless. The default value is 0.7.

**gammaCValue:** ***float, optional***

Specify the adiabatic index of the lobe plasma. The default value is 5.0/3 for a non-relativistic fluid.

**lorentz_min:** ***string, optional***

Specify the minimum Lorentz factor of electron energy distribution at time of shock acceleration.

**resolution:** ***string, optional***

Specify resolution, and correspondingly the number of Lagrangian particles, used in surface brightness images. Permitted resolutions are 'best', 'high', 'standard' and 'poor' which correspond to 114 688 000, 28 672 000, 7 168 000 and 1 792 000 particles respectively. The default value is 'standard'.

**seed:** ***string or float, optional***

Specify a seed for the psuedo-random number generator used to produce gas density profiles for the host environment. This parameter is only required if `rand_profile=True`. No seed is provided by default.

**rerun:** ***string, optional***

If this line is existent, rerun = 'True' will tell RAiSE to rerun the code. The default value is False.

**labels:** ***string, optional***

Specify whether labels are wanted on evolutionary tracks graph. The default value is none.

**colors:** ***string, optional***

Specify colours of evolutionary tracks graph. The default value is none.

**linestyles:** ***string, optional***

Specify style of lines on evolutionary tracks graph. The default value is a solid line.

## Examples

### Running a singular simulation

Simulation of a radio AGN observed at 1.4GHz, jet power of $10^{38.8}, redshift of 0.1,$

#### Custom environment

To instead simulate a custom gas density profile, halo mass is no longer required, and instead values for random profile, rho0Value, betas, regions and temperature must be specified.

```
>>> RAiSE.RAiSE_run(9.146, 0.1, 2.8, 38.8, [7,8], rho0Value=1e-23, betas=[1,1.9],
regions=[1,100] temperature=1e7, brighness= False)
```

#### Creating a surface brightness map

Generating a surface brightness image. Resolution options of 'best,' 'high,' 'standard' and 'poor.' These resolutions corresponds to 114 688 000, 28 672 000, 7 168 000 and 1 792 000 particles respectively.

```
>>> RAiSE.RAiSE_run(9.146, 0.1, 2.8, 38.8, 7, halo_mass=13.5, resolution = 'high')
```

Can be found in LD_Tracks folder. Horizontally will show values from minor axis (kpc) and vertically the grid will show values from the jet axis (kpc). Data values will represent the brightness of pixels in units of Watts per Hertz.

#### Running a grid for parameter lists

Parallelised code that is generating evolutionary tracks or surface brightness images. Any of the parameters defined in the above pages as lists or arrays can be used here.

```
>>> RAiSE.RAiSE_run(9.146, [0.1,0.5,1], 2.8, [38,39,40] , 7.5, halo_mass=13.5, brightness = True)
```

**Plotting luminosity maps** Shown in Figure 1.

```
>>> RAiSE.RAiSE_evolution_maps(8.146, 0.1, 2.8, 38.8, 7.5, jet_lorentz=5, halo_mass=13.5,
rerun=False)
```

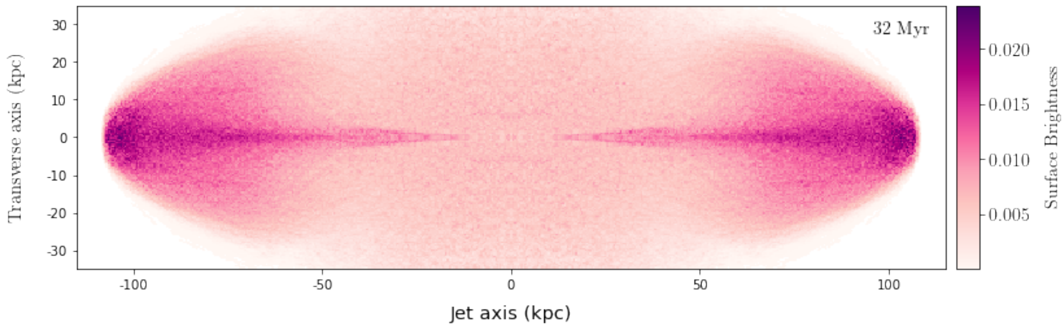


**Figure 1.** Luminosity Map

When rerun = False, and the same simulation has be conducted, it will take significantly less time as it has already run and will not need to try and redo the code.

**Plotting evolutionary tracks**

Must input multiple source ages. This example uses singular parameter inputs for the rest. Input rerun = True to over right any existing evolutionary tracks file for this set of parameters. Shown in Figure 2.

```
>>> import numpy as np
>>> RAiSE.RAiSE_evolution_tracks(9.146, 0.1, 2.8, 38.8, np.arange(6,8.5,0.1), jet_lorentz=5,
halo_mass=13.5, resolution='poor', rerun=True)
```

This example uses multiple jet powers. Shown in Figure 3.

```
>>> fig=RAiSE.RAiSE_evolution_tracks(9.146, 0.1, 2.8, [38,39], np.arange(6,8.5,0.1),
jet_lorentz=5, halo_mass=13.5, rerun=False, resolution='poor',
labels['$Q=10^{38}$_W','$Q=10^{39}$_W'], colors=['purple','green'], linestyles = ['--',':'])
```

When using multiple jet powers, labels for each are useful to distingusih between the two. Colours are also able to be altered, using a list of colors defines each jet power to have those colours, linestyles are also similar, they can be altered and listed.

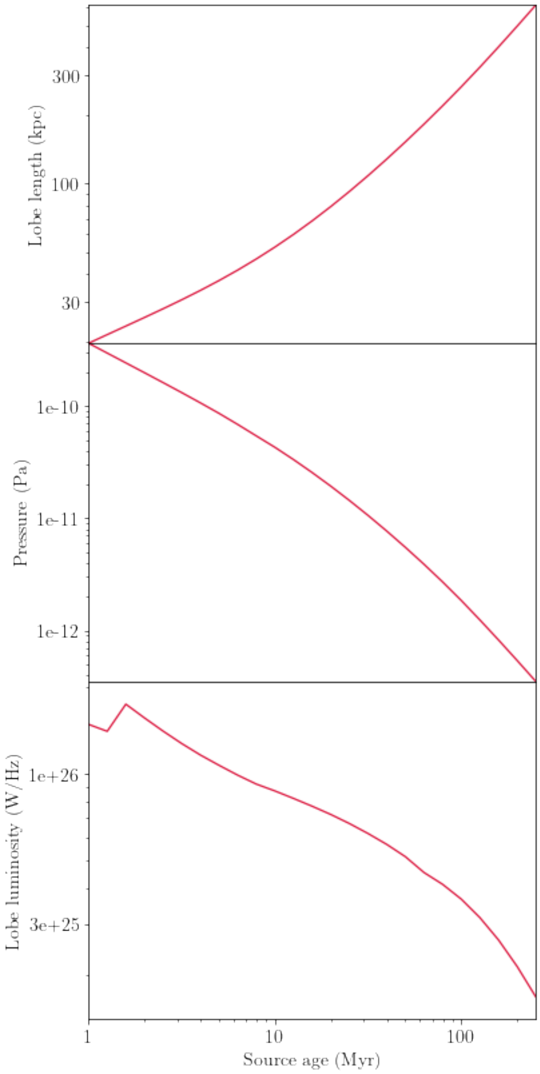


**Figure 2.** Luminosity Map

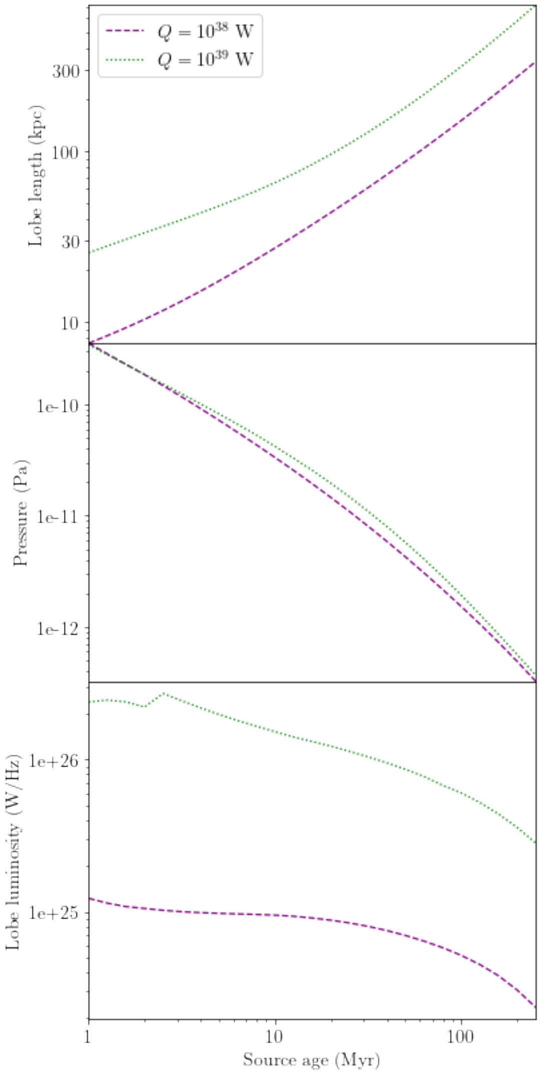


**Figure 3.** Luminosity Map with multiple Jet Powers