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A radiative transfer algorithm to calculate the spectral evolution in relativistic jets

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Abstract. A major challenge in the study of relativistic jets is the determination of the jet plasma's physical state, such as density, pressure, velocity or magnetic field from the observed radio synchrotron emission by the non-thermal particles. When predicting emission maps and spectra from relativistic jets, it is important to consider special relativistic Doppler boosting and time delays between different emission region, non thermal radiative losses by the emitting particles, modulation by the intermediate space between the source and the observer by Faraday rotation and opacity, particle acceleration at shocks, magnetic reconnection. Magneto-hydrodynamic simulations need to be complemented by additional schemes that track the evolution of the non-thermal particle distribution and perform the ray tracing taking into account all the above-listed effects. In this first stage, we evolve a power-law particle distribution in post-process considering the adiabatic changes and frequency dependent synchrotron radiative losses of the non thermal electrons. We apply our synthetic radio emission calculations to simulations of relativistic jets with the hydrodynamical code PLUTO. The simulations include models of the radio galaxy Hydra A focussing on the role of spectral evolution in the brightness of inner knots, and the flaring zones.

Resumo. Um grande desafio no estudo de jatos relativísticos é a determinação do estado físico do plasma do jato, tais como densidade, pressão, velocidade ou campo magnético a partir da emissão radiossincrotrônica observada pelas partículas não térmicas. Na previsão de mapas e espectros de emissão de jatos relativísticos, é importante considerar o aumento estimulante Doppler relativista e atrasos de tempo entre diferentes regiões de emissão, perdas radiativas não térmicas pelas partículas emissoras, modulação pelo espaço intermediário entre a fonte e o observador pela rotação e opacidade de Faraday, aceleração das partículas nos choques, reconexão magnética. As simulações magneto-hidrodinâmicas precisam ser complementadas por esquemas adicionais que acompanhem a evolução da distribuição de partículas não térmicas e realizem o rastreamento de raios levando em consideração todos os efeitos acima mencionados. Nesta primeira etapa, desenvolvemos uma distribuição de partículas de poder em pós-processo considerando as mudancas adiabáticas e as perdas radiativas dependentes da frequência de sincronismo dos eletrons não-térmicos. Aplicamos nossos cálculos sintéticos de radioemissão a simulações de jatos relativísticos com o código hidrodinâmico PLUTO. As simulações incluem modelos da radiogaláxia Hydra A focando o papel da evolução espectral no brilho dos nós internos e as zonas de fulguração.

Keywords. Galaxies: jets – Radiative transfer – Methods: numerical

1. Introduction

Relativistic jets are collimated magnetised flows emanating from the vicinity of central supermassive blackholes of active galactic nuclei. They can extend from few tens of Schwarzschild radii to very large ten to hundreds kilo parsec scale structures. Modern powerful supercomputers allow us to perform detailed numerical hydrodynamic modelling of jets from parsec to kpc scale. However, incorporation of non-thermal particle evolution and radiative transfer in the hydrodynamic calculation is still computationally challenging because it introduces additional dimensions (particle energy, frequency and direction of radiation) to the problem. Furthermore, because the timescale associated with the transport microphysics is often smaller than the dynamic timescale of the jet, subgrid recipes, for example for shock acceleration, need to be invoked. Therefore, alternative post-process calculations of the evolution of non-thermal particle distributions and associated non-thermal emission have been used to study relativistic jets (Komissarov & Falle 1996; Mimica et al. 2009; Nawaz et al. 2014, 2016).

In this study, our goal is to set up a numerical scheme to calculate spectral evolution of non-thermal particles in relativistic jets and apply this to new simulations using the hydrodynamic code PLUTO. In particular, we shall revisit the internal and global structure of the Hydra A radio galaxy, an archetypal precessing FRI radio source in a cool core cluster. We use a Lagrangian scheme for calculating the transport of non-thermal particles, based on that of Mimica et al. (2009). In this method, the distribution of the non-thermal particles is tracked in both spatial and energy space. The initial positions of the NTPs, at the jet base, advect following the background velocity field while the energy space and the particle distribution evolve according to

$$\frac{dp}{dt} = a(t)p + b(t)p^2 \tag{1}$$

where, p is the momentum of NTP. Factors $a(t)$ and $b(t)$ account for the adiabatic and synchrotron losses, respectively. The NTP distribution is discretized in the energy domain and approximated by a The synchrotron emissivities and absorption coefficients are calculated directly from the NTP distribution and the thermodynamic quantities of the background relativistic fluid. Finally, we will compute emission solving the radiative transfer equation along the line of sight.

2. Jet intracluster medium interaction

We develop an axisymmetric model for a magnetised relativistic jet interacting with the intracluster medium (ICM). The jet parameters are set by a constant jet power P_{jet}, that is related to

Table 1. Summary of simulation parameters.

Parameter	Value
Jet Power, $P_{\rm jet}$	10^{45} erg/s
Jet inlet radius, $r_{\rm jet}$	0.1 kpc
Jet density parameter , $\chi_{\rm jet}$	12.67
Jet over pressure ratio, $p_{\rm jet}/p_{\rm a}$	5
Lorentz factor, Γ	1.7
Plasma $\beta = 2p_{\rm jet}/B^2$	10

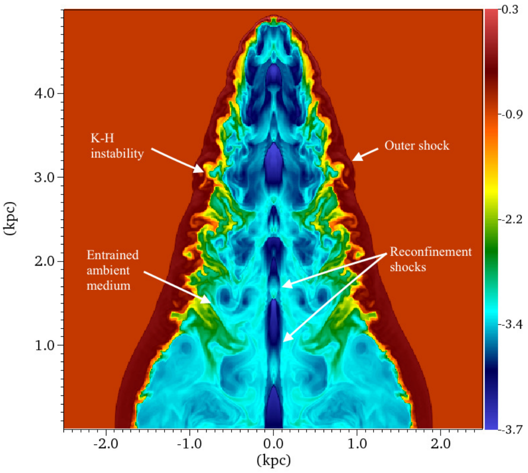

Figure 1. Logarithmic density snapshot of the jet-ICM interaction model. Biconical reconfinement shocks form as the jet expands and interacts with the environment. At the contact discontinuity Kelvin-Helmholtz instability develops.

other jet parameters, such as, jet cross-section $A_{\rm jet} = \pi r_{\rm jet}^2$, where $r_{\rm jet}$ is the jet inlet radius, jet pressure $p_{\rm jet}$, jet density parameter $\chi_{\rm jet} = \rho_{\rm jet} c^2/(p_{\rm jet} + \varepsilon_{\rm jet})$, where $\rho_{\rm jet}$ and $\varepsilon_{\rm jet}$ are the rest mass density and internal energy density of the jet, jet velocity $v_{\rm jet}$, jet Lorentz factor Γ and the magnetic field B^i.

$$P_{\rm jet} = A\left[\frac{\gamma}{\gamma-1} p_{\rm jet}\Gamma^2 v_{\rm jet}\left(1+\frac{\Gamma-1}{\Gamma}\chi_{\rm jet}\right) + \Gamma^2 B^2 v^i - B^i v_i B^i\right] \qquad (2)$$

Here, γ is the adiabatic index. We set a hydrostatic environment based on the X-ray data of the Hydra A cluster. The jet is initialised with best fit values obtained from a previous study of the source (Nawaz et al. 2014).

The simulation parameters are summarised in Table 1. Different features developed in the earlier stage of jet evolution are shown in the logarithmic density slice in Figure. 1.

3. Synchrotron emission map

We are in the initial stage in developing the spectral evolution code. However, we produce a synthetic radio map from the estimated Stokes synchrotron emissivity for each cell assuming that the nonthermal particle pressure is proportional to thermal pressure (Wagner & Bicknell 2011). Here we consider the effects of relativistic aberration and Doppler boost. This method does not consider particle transport, nevertheless, it successfully captures features like bright inner jet knots and terminal hot spot. Figure. 2 shows synthetic radio map of the modelled jet at a line of sight angle 90°.

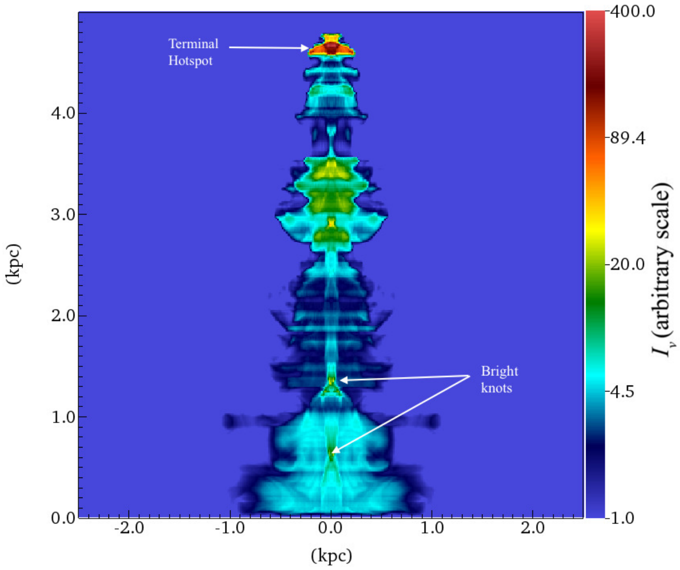

Figure 2. Synthetic radio map of the axisymmetric model. Inner bright knots develop due to reconfinement shocks and a terminal hotspot develops where the jet hits the cavity wall.

4. Summary

In the first stage of our study we develop an axisymmetric jet-ICM model. The key features we obtain with our model are: i) bright knots, ii) outer shock, iii) terminal hotspot and iv) entrainment layer of shocked jet and ambient plasma.

Once developed, the spectral evolution code will be incorporated with the hydrodynamical output to calculate emission from relativistic jets. Focussing on a prominent radio galaxy Hydra A, we will utilise the algorithm to study the role of evolutionary history of nonthermal particles on the observed jet features. This code will be an efficient tool to study two poorly understood features of Hydra A jets: i) The increasing brightness of inner jet knots along the jet axis, and ii) The bright zones where the initially collimated jets flare to form wide plumes.

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