Large Scale Simulations of Jets
in Dense and Magnetised Environments

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We have used the vectorised and parallelised MHD code NIRVANA on the
NEC SX-5 in parallel mode to simulate the interaction of jets with a dense
environment on a scale of more than 200 jet radii. A maximum performance
of 0.75 GFLOP per processor could be reached.

One simulation is axisymmetric and purely hydrodynamic, but with a
resolution of 20 points per beam-radius (ppb). The bipolar jet is injected in
the center of a spherically symmetric King profile, initially underdense to its
environment by a factor of 10,000. As expected from our previous work, the
jet starts with producing a spherical bubble around it, bounded by the bow
shock. The bubble slowly elongates, first with roughly elliptical shape, and
then forms narrower extensions in beam direction. The final aspect ratio of
the bow shock is 1.8. We have transformed the results on a 3D-rectangular grid
and integrated the emission properties to compare the results with observed
central cluster radio galaxies. In the particular case of Cygnus A, we come to
convincing consistency, morphologically, regarding the size of the influenced
region by the jet, size, and cylindrical shape of the radio cocoon, and source
age. This strongly supports our earlier hypothesis on the nature of the jet in
Cygnus A, and the derived constraints on other jet parameters like a power of
$8 \times 10^{46}$ erg/s and an age of 27 Myr. But, the simulation also clearly shows the
shortcoming of the model: The jet’s beam is very unstable, reaching the tip
of the bow shock only very seldom. Also, the contact discontinuity between
shocked beam plasma and shocked ambient gas is quite disrupted by the
action of the Kelvin-Helmholtz-instability. This is not seen in observations,
and necessitates the presence of dynamically important magnetic fields or an
at least moderately relativistic flow, or both.

The other simulation was designed to explore the impact of a jet on a
randomly magnetised environment. A bipolar jet is injected into a King profile
on a 3D Cartesian grid, with a resolution of 3 ppb. This simulation was not
successful, because the timestep became too low after 0.7 Myr The preliminary
results show no increase of the magnetic fields reversal scale yet, which was
expected from an unpublished 2D slab jet simulation, but not that early.
1 Introduction

Several billion years ago, at redshifts in excess of two, the centers of galaxy clusters, typically hosting already a relaxed elliptical galaxy with an old population of stars, were usually equipped with a powerful radio jet. There are many different lines of evidence for this (Carilli et al. 2001). The host galaxies of radio jets are the brightest ones at their redshift. Also, there have been found dozens of line emitting objects around five high redshift radio galaxies, so far (Venemans et al. 2003). This is a significant overdensity. Furthermore, the space density of galaxy clusters at low redshift agrees with that of high redshift radio galaxies. Hence it is clear that radio galaxies pinpoint the most massive structures in the high redshift universe.

Contrary to the situation at high redshift, the brightest cluster galaxies (BCGs) in the local universe are generally associated only with weak radio jets. The only exception being Cygnus A (Fig. 2a). This classical double radio galaxy has an outstanding power, only reached by sources with redshifts in excess of roughly unity. The affected gas surrounding the radio jet can be observed in great detail in the X-ray regime by the Chandra satellite. Therefore, Cygnus A can serve as a model for the interaction of the jet with the intergalactic medium (IGM), for powerful, classical double radio jets. Much work has been done on the propagation of extragalactic jets (compare e.g. Krause & Camenzind 2001; Krause 2003, and references therein). Of particular interest for the present study are simulations that include all the external gas that is affected by action of the jet (Clarke et al. 1997; Reynolds et al. 2001, 2002; Saxton et al. 2002a,b; Krause & Camenzind 2002b,c; Krause 2002a, 2003; Zanni et al. 2003). These simulations did not yet reach the actual size of the jet in Cygnus A, but could be extrapolated to derive a hydrodynamical model of the jet (Krause 2002b; Krause & Camenzind 2002c). In this model, the jet in Cygnus A resides in a stratified galaxy cluster atmosphere, with a central density contrast (jet/IGM) of roughly $10^{-4}$. We have tested this model with a large scale simulation that we report in sect. 2. The radio emission of jets has been applied to study the large scale coherence of magnetic fields in galaxy clusters (e.g. Dolag et al. 2002). We propose the idea that the magnetic field is randomly oriented, but with roughly the same plasma $\beta$ everywhere, before the jet passes. We have already shown, that a slab jet with similar parameters as used here, produces a coherent field structure in the shocked ambient gas (unpublished), with reversal scales of 10 to 50 $R_j$, when simulated up to a diameter of 400 $R_j$. In order to check the validity of this result in 3D, we tried to accomplish such a simulation. The results are described in sect. 3.

1.1 Numerics

For the computations in this contribution, the magneto-hydrodynamic (MHD) code *Nirvana* was employed. The main part of this code (*NIRVANA*) was written by Udo Ziegler (Ziegler & Yorke 1997). In that version, it solves the
MHD equations in three dimensions (3D) for density $\rho$, velocity $\mathbf{v}$, internal energy $e$, and magnetic field $\mathbf{B}$:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{1}
\]
\[
\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p - \rho \nabla \Phi + \frac{1}{4\pi} (\mathbf{B} \cdot \nabla) \mathbf{B} - \frac{1}{8\pi} \nabla \mathbf{B}^2 \tag{2}
\]
\[
\frac{\partial e}{\partial t} + \nabla \cdot (e \mathbf{v}) = -p \nabla \cdot \mathbf{v} \tag{3}
\]
\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) \tag{4}
\]

where $\Phi$ denotes an external gravitational potential.

NIRVANA can be characterised by the following properties:

1. explicit Eulerian time-stepping,
2. operator-splitting formalism for the advection part of the solver,
3. method of characteristics-constraint-transport algorithm to solve the induction equation and to compute the Lorentz forces;
4. artificial viscosity has been included to dissipate high-frequency noise and to allow for shock smearing in case the flow becomes supersonic.

The code was vectorised and parallelised by OpenMP like methods, and successfully tested on the SX-5 (Krause & Camenzind 2002a). All the significant loops could be vectorised. The number crunching part scales without significant performance loss. This is also true for the MHD part of the solver. We show a typical profile output below (Tables 1 and 2), for a run without data output, which indicates an optimum in vectorisation and parallelisation efficiency. The average performance in the 2D simulation was only 434 cumulative MFLOPS with eight processors, probably because in this run, about 500 GB of data had to be dumped to the hard disk, which is a serial process.

### 2 Simulation of a Very Light Jet to Large Scale

We have performed a bipolar axisymmetric simulation – in the following called run A – of a very light jet in a King type galaxy cluster atmosphere with a

![Fig. 1. Performance for the 3D-MHD problem. The vectorised loops contained 512 cells, and the parallelised ones 224 cells. With that parameters, the code scales very good.](image-url)
Table 1. Typical profile output: Program Information

|                  | Value                      |
|------------------|----------------------------|
| Real Time (sec)  | 196.546238                 |
| User Time (sec)  | 1121.74682                 |
| Vector Time (sec)| 941.991913                 |
| V. Inst. Count   | 29681221986                |
| V. Element Count | 313399958530               |
| FLOP Count       | 851661050792               |
| MOPS             | 2808.824657                |
| MFLOPS           | 759.227487                 |
| Memory Size (MB) | 3216.000000                |
| Max Concurrent Proc. | 12                       |
| Conc. Time(>=1) (sec) | 95.228785                |
| Conc. Time(>=2(>=4) (sec) | 94.162890                |
| Conc. Time(>=5) (sec) | 94.044669                |
| Conc. Time(>=8) (sec) | 94.009968                 |
| Conc. Time(>=10) (sec) | 93.883754                |
| Conc. Time(>=12) (sec) | 86.836165                |
| Event Busy Count | 0                          |
| Lock Busy Count  | 1223                       |
| Barrier Busy Count| 0                          |
| MIPS             | 26.459822                  |
| I-Cache (sec)    | 1.106138                   |
| O-Cache (sec)    | 33.629114                  |
| Bank (sec)       | 23.186143                  |

Table 2. Typical profile output: Multitasking Information

| Seconds | Seconds | Thread/Macro[tid] |
|---------|---------|-------------------|
| %Res.   | Res.    | T/M               | Micro| %CPU | CPU | CPUCum. | Wait | -micro[n] |
| 0.0     | 93.66   | 0.04              | 8.4  | 93.62| 93.66| 0.77    | -micro1|
| 100.0   | -       | -                 | 8.3  | 93.15| 186.81| 0.28   | -micro2|
| 99.5    | -       | -                 | 8.3  | 93.16| 280.42| 0.00   | -micro3|
| 99.9    | -       | -                 | 8.3  | 93.16| 373.57| 0.32   | -micro4|
| 99.5    | -       | -                 | 8.3  | 93.11| 466.68| 0.22   | -micro5|
| 99.4    | -       | -                 | 8.3  | 93.14| 559.82| 0.21   | -micro6|
| 99.3    | -       | -                 | 8.3  | 93.02| 652.84| 0.30   | -micro7|
| 99.4    | -       | -                 | 8.3  | 93.13| 745.97| 0.31   | -micro8|
| 99.6    | -       | -                 | 8.3  | 93.26| 839.22| 0.27   | -micro9|
| 99.5    | -       | -                 | 8.3  | 93.16| 932.38| 0.32   | -micro10|
| 99.2    | -       | -                 | 8.3  | 92.93| 1025.31| 0.26  | -micro11|
| 99.5    | -       | -                 | 8.3  | 93.18| 1118.49| 0.30  | -micro12|

%Res.: The residence ratio.
Res.: The residence time.
T/M: The CPU time of thread/macrotask.
Micro: The CPU time of microtask.
%CPU: The CPU ratio of thread/macrotask or microtask.
CPU: The CPU time of thread/macrotask or microtask.
CPUCum.: The cumulative CPU time.
Thread/Macro[tid]: The thread/macrotask and microtask identifier.
final jet size of > 200 jet radii. The simulation was run for 6200 CPU hours on eight processors of the SX-5 at the HLRS.

2.1 Simulation Setup

The jet was injected in both directions (bipolar) in the center of a cylindrical grid with 8300 and 2000 points in axial (Z) and radial (R) direction, respectively. The basic length scale of the problem is the jet radius which is represented by 20 points. With that resolution global parameters like the bow shock velocity on the Z-axis or energy and momentum conservation are accurate to ≈ 10% (Krause & Camenzind 2001). As our unit of length we choose the observed jet radius in Cygnus A, i.e. the jet radius is set to \( R_j = 0.5 \) kpc. The total grid size is therefore \([207.5 \times 50]\) kpc. The environmental density \( \rho_e \) is given by an isothermal King profile:

\[
\rho_e(R, Z) = \rho_{e,0} \left(1 + \frac{r^2}{a^2}\right)^{-3\beta/2},
\]

where \( r^2 = R^2 + Z^2 \). This means that the density is constant up to a core radius \( a \) that was set to \( a = 10 \) kpc. Then it starts to decrease, asymptotically reaching \( \rho_e \propto r^{-3\beta} \) (\( \beta = 3/4 \)). The central density was set to \( \rho_{e} = m_H c m^{-3} \), with the hydrogen mass \( m_H = 1.67 \times 10^{-24} \) g. The temperature was set to \( T = 30 \) Mio. K. This atmosphere is kept in hydrostatic equilibrium by the gravity of a dark matter halo:

\[
\Phi = \frac{3\beta k T}{2 \mu m_H} \log \left(1 + \frac{r^2}{a^2}\right).
\]

\( \mu \) is the number of particles per proton mass. Here, \( \mu = 0.5 \) for an ionised medium. In order to brake the symmetry, density perturbations were included, i.e. with 10% probability, the density in a cell was increased by a random factor between 0 and 40%. The jet density was set to \( \rho_j = \eta_0 \rho_j \), with the density contrast \( \eta_0 = 10^{-4} \). The sound speed in the jet was set to 20% c, c being the speed of light, and the jet’s Mach number to \( M = 3 \).

The simulation was run for 20 Myr, in total. During that time, the jet reached an extension of 110 kpc, i.e. 220 jet radii, on the axis.

2.2 Results

We present logarithmic density plots of the simulation results for four different simulation times (5, 10, 15, 20 Myr) in Fig. 3. The morphology that appears in these figures is a continuation of previous simulations that could not reach the size shown here. Fig. 3a shows the state that was reached by Krause (2003), and extensively discussed therein. In this early phase, the bow shock is spherical, its radius following an expansion law given by the force balance
Fig. 2. (a) The nearby radio galaxy Cygnus A. Colours show the logarithmic intensity of the 5 GHz radio image (VLA, credits: NRAO / AUI / NSF). Contours show the adaptively smoothed X-ray emission (Chandra satellite, credits: NASA / UMD / A.Wilson et al., courtesy: P. Strub). The axis shows the length scale at the luminosity distance of Cygnus A (246 (h/0.7) Mpc), where h denotes the Hubble constant in units of 100 km/s/Mpc. The jet beam is created at the origin of the coordinate system where the active center of the host galaxy is located. Two barely visible, narrow beams emerge from there in opposite directions, powering the hotspots at (-60,-25) and (70,30). The beam plasma then assembles in a cylindrical cocoon, at lower radio surface brightness. Lower frequency images show that the cocoon continues through the empty region in the center. It removes and compresses the IGM, shaping it elliptically. (b) The radio galaxy 4C 41.17 at redshift 3.8, corresponding to a lookback time of 12 billion years. The gray scale shows the Lyman α emission line nebula, the contours represent the 5 GHz radio emission. The white cross indicates the radio core, i.e. the region where usually the active center of the galaxy is located. Adopted from astro-ph: 0303637. Courtesy: Wil van Breugel. (c) Bow shock position at Z=0 versus time for the simulation in sect. 2. The three fits are: 2.57017+2.13717(0.859365) (global fit), 7.34264+0.960744t(1.06464) (15-20 Myr), and 2.59878+2.27161(0.821546) (4-6 Myr). (d) Bow shock extension on the axis versus time for the simulation in sect. 2. The three fits are: 8.39571+2.51264t(1.23664) (global fit), 3.73811+2.92394t(1.20278) (14-20 Myr), and 5.39429+4.71728(0.956775) (4-6 Myr).
equation which can be integrated to yield, for arbitrary mass distribution $\mathcal{M}(r)$ and energy injection $E(t)$:

$$
\int_{0}^{r} \mathcal{M}(r_1) r_1 dr_1 = 2 \int_{0}^{t_1} dt_1 \int_{0}^{t_1} E(t_2) dt_2.
$$

For the given matter profile (5), (7) can be integrated numerically. We only discuss the asymptotic power law parts here. For a power law density distribution ($\rho = \rho_0 (r/r_0)^\kappa$) and constant energy injection ($E = Lt$), the solution is:

$$
r = \sqrt[\frac{2(\kappa+3)(\kappa+5)}{12\pi\rho_0} Lt^3].
$$

The density profile used here has the asymptotic power law approximations: $\lim_{r \to 0} (\rho) = \rho_0$, and $\lim_{r \to \infty} (\rho) \propto r^{-9/4}$. Therefore, the bow shock should expand with $r \propto t^{6.6}$ in the beginning, steepening towards $r \propto t^{1.09}$, at least as long as it remains spherical. The radial bow shock position was determined every 0.4 Myr (compare Fig 2c).
It was fitted with a function \( r = a + b t^c \), where \( a, b, \) and \( c \) were simultaneously varied. At \( \approx 5 \) Myr, where the bow shock is still almost spherical (aspect 1.2), \( c \) is 0.82. The expected exponent, using a local power law approximation for the density and the analytic approximation, is: \( c_{\text{theo}} = 0.79 \). This confirms the analytic approximation. But the bow shock continues to follow this expansion law far beyond the spherical phase: at \( \approx 17.6 \) Myr, the fit gives \( c = 1.06 \) versus 1.00 from the analytic model. Even a global power law, with exponent 0.86 fits quite good.

The propagation in axial direction is shown in Fig. 2d. Besides the early times, the bow shock always accelerates. Its acceleration \( (v \propto t^{0.2}) \) is always significantly higher than predicted by self-similar modelling (asymptotically: \( v \propto t^{0.9} \)) (compare e.g. Carvalho & O’Dea 2002, and references therein), but does not reach the prediction for narrow beams of constant radius that would be super-exponential for \( \kappa < -2 \).

This reflects the state of the beam plasma. Figure 3 shows a sound beam, reaching to the tip of the bow shock, only for \( t < 10 \) Myr. At later phases, the beam is disrupted towards the head. Thereby, the beam thrust is distributed over a greater area, leading to lower bow shock velocity compared to the case of a narrow beam with constant radius.

The cocoon transforms gradually from conical to cylindrical at later times. Its width does not grow much for the second half of the simulation. Towards the center, there is a turbulent region, where the ambient gas is entrained into the cocoon by the action of gravity, and mixed with the shocked beam plasma.

### 2.3 Comparison to Observations

The prime target to compare the simulation data to is the X-ray data of Cygnus A (compare Fig. 2a). The simulation was run to almost the size of the real source (110 kpc and 140 kpc, for simulation and observation, respectively). It is evident from Fig. 3 that this is necessary in order to get the correct cocoon morphology. Many other details can be understood by this new simulation: Fig. 2a shows that the radio cocoon is bordered by the brightest X-ray emission. We show the line-of-sight integrated X-ray emission for the simulation together in Fig. 3d. These can be compared directly to the observations in Fig. 2. The simulation clearly shows the peaks in emission next to the radio cocoon. This was already predicted analytically, in self-similar models (Alexander 2002). Outwards of this peak, the emissivity is increased with respect to the undisturbed cluster emission, by a constant factor in the plane of symmetry. The emission falls suddenly at the bow shock. This detail cannot be seen in the observational data, because there are not enough photons (but compare Fig. 4 in Smith et al. (2002)). Fig. 3d shows that the emission of the shocked ambient gas has been shaped by the bow shock in an elliptical way. Smith et al. (2002) have shown that the elliptical isophotal fit is better than
the spherical fit inside a radius of $66/(h/0.7)$ kpc, which should indicate the bow shock’s radial position in Cygnus A.

The simulation shows significant emission in the mixing region in the central parts of the cocoon. However, this is less than observed. The reason is numerical mixing with cocoon gas in that region. Also, the observation shows dominantly non-axisymmetric modes, which cannot be represented in our axisymmetric simulation. We note that this region has been found to be non-axisymmetric in 3D simulation (Krause & Camenzind 2002a).

It has been suggested that repeated jet episodes could heat the surrounding gas to the observed X-ray temperatures during cosmological timescales. A lower limit to the heat injection in the cluster gas was derived by Krause (2003), equ. (21). For the simulation parameters here, this lower limit amounts to $3.19 \times 10^{58}$ erg. The cluster gas was followed by a passive tracer that was set to unity. Counting only cells where the tracer variable is above 0.1, we measure $8.17 \times 10^{59}$ erg internal energy injected by the jet into the cluster gas by the end of the simulation. The cluster gas has also gained $2.37 \times 10^{60}$ erg of potential energy. In total, 69% of the energy injected by the jet has been put into the ambient gas. This is enough to power the X-ray emission of the cluster in Cygnus A for $\approx 500$ Mio. years. This makes it entirely plausible that the cluster gas is heated by that mechanism.

We have proposed to measure jet parameters based on the radial bow shock propagation. The radial bow shock velocity in Cygnus A can be constrained from the shock temperature measured by Chandra (Krause & Camenzind 2002c). This procedure gives a jet power of $L = 8 \times 10^{46}$ erg/s and an age of $t = 27$ Myr for Cygnus A. In order to demonstrate the validity of the procedure, we determine the jet parameters for the simulation in the same way. The simplest approximation for the external density is taking it to be constant. Then, from (8) it follows with the bow shock velocity of 1220 km/s, the radial bow shock position 30.17 kpc and the external density of $10^{-25}$ g/cm$^3$: $L = 9.96 \times 10^{45}$ erg/s and $t = 19.7$ Myr. This is to be compared to the true jet power, $L_{\text{true}} = \pi R_{\text{j}}^2 \rho_{\text{j}} v_{\text{j}}^3 = 7.72 \times 10^{45}$ erg/s and the true jet age of 20 Myr. This very good agreement demonstrates that the exact shape of the cluster atmosphere is not critical in determining jet parameters. The agreement can even be improved by taking better approximations to the density profile.

The simulation result shows an important difference to the observation: In the simulation, the beam is very unstable, reaching the tip of the bow shock not even once, after 10 Myr. The reason for this is the low Mach number in the beam that is a consequence of the strong interaction with the cocoon and the entrained shocked ambient gas therein. Higher Mach numbers can only be reached by a relativistic jet. However, the beam could also be stabilised by an appropriate, significant magnetic field. The magnetic field is also demanded in order to preserve the contact discontinuity near the tip of the bow shock from the action of the Kelvin-Helmholtz-instability, because the strong disruption found in the simulation can not be found in the radio data. This result is in good agreement with with magnetic field determinations in Cygnus A’s hot
spots via the self-synchrotron-Compton assumption (Wilson et al. 2000) and our earlier suggestion, based on a jet power argument, that the jet’s mean Lorentz factor is $\Gamma \approx 20$.

2.4 Comparison to High Redshift Radio Galaxies

So far, high redshift radio galaxies have not been observed long enough in order to study the cluster gas emission in great detail. But the region where the shocked ambient gas could be expected is typically bright in emission lines. The emission line regions often have the same cone shaped structure as the X-ray emission in Cygnus A (compare Fig 2a and 2b). The line emission is brightest in the region, corresponding to the mixing region in the simulation. This could be interpreted in the way that in these objects the line emission is caused by material that was entrained into the radio cocoon.\(^1\) This gas is subject to the combined thermal and Rayleigh-Taylor instability, which may cool some gas to the appropriate temperatures (Basson 2002; Krause 2002b).

3 A Jet in a Randomly Magnetised Environment

We have accomplished a 3D simulation of a jet in a randomly magnetised environment. The simulation run for 500 CPU hours on eight processors of the SX-5. Unfortunately, the timestep became too low, before significant evolution of the jet could be seen.

3.1 Numerical Setup

We injected the jet in the center of a Cartesian grid ($[X \times Y \times Z] = [170 \times 74 \times 74]$ kpc = $[512 \times 224 \times 224]$) in the X direction. The jet radius was set to $R_j = 1$ kpc and resolved with 3 points. The magnetic field at the jet inlet was set to zero for the $Y$ and the $Z$ direction, and $\partial B_X/\partial x = 0$ on the jet nozzle. In the surrounding King atmosphere ($\rho_{e,0} = m_p/10$, $a = 10$ kpc, and $\beta = 2/3$, $T = 3 \times 10^7$ K), a random magnetic field was established. The vector potential was randomly determined, folded with the King distribution in order to get an average plasma $\beta$ of $\beta = 8 \pi p/B^2 = 12$, i.e. sub-equipartition fields. The initial density contrast was set to $\eta = 10^{-3}$ and the Mach number to $M = 5$.

\(^1\) The alternative interpretation is that cooling is significant in the whole shocked ambient gas region. This would lead to very large cocoon width and turbulent mixing of radio plasma and emission line gas (Krause 2002a). Most recent X-ray data for 4C 41.17 (Scharf et al. 2003), showing probably inverse Compton cocoon emission, point in this second direction for that particular object.
Fig. 4. Results of the 3D simulation with randomly magnetised environment at $t = 0.7$ Myr. a: density slice at $Z=0$, b: plasma beta at $Z=0$.

3.2 Results and Discussion

A slice of the density distribution and the plasma $\beta$ is shown in Fig. 4. In that phase, the bow shock is already weak. Weak MHD shocks reduce the field strength and refract the field towards the shock normal. The simulation shows a decrease of the magnetic field of typically an order of magnitude, behind the bow shock, yet. Unfortunately the simulation could not be run for longer time, since the timestep became too low. In that phase, no amplification of the reversal scale could be found, as in a slab simulation (compare sect. 1). This probably happens only when the shocked ambient gas expands to several times the cocoon diameter, like e.g. in Fig. 3d. If this effect could be confirmed, it would be a good candidate for the explanation of the high reversal scale in galaxy clusters, i.e. the coherence of the field is created by the weak bow shock.

4 Conclusions

Employing the NEC SX-5 supercomputer at the HLRS, we could simulate an axisymmetric jet to the large extent of more than 200 jet radii. On that scale, the results can be directly compared to observational data of Cygnus A. Many details, like elliptically shaped emission, morphology of cocoon and shocked ambient gas, or low aspect, are well reproduced. This confirms the hypothesis that the jet is underdense with respect to its environment by a factor of $\approx 10,000$, and the consequences on the jet parameters discussed above. We also find differences to the observational data, concerning stability of the beam and the contact discontinuity, which we ascribe to the missing magnetic fields and the disregard of relativistic physics. We speculate that emission line halos of high redshift radio galaxies might be identified with the centrally concentrated mixing region in the cocoon.

We also tried to simulate the influence of the jet on a randomly magnetised environment. Unfortunately, the timestep became too low, and the simulation had to be stopped, before significant progress has been made.
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