Parameters for Very Light Jets of cD Galaxies

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Abstract

Recent Chandra X-ray observations of jets in central cluster galaxies show interesting features around the symmetry plane. We have carried out simulations involving bipolar jets, removing the artificial boundary condition at the symmetry plane. We use a very low jet density (IGM/jet $\approx 10^4$) and take into account a decreasing density profile. We find that the jet bow shock undergoes two phases: First a nearly spherical one and second the well-known cigar-shaped one. We propose Cygnus A to be in a transition phase, clear signs from both phases. Due to inward growing of Kelvin Helmholtz instabilities (KHI) between cocoon and shocked IGM, mass entrainment is observed predominantly in the symmetry plane. We propose this mechanism to produce some of the so far enigmatic X-ray features in the symmetry plane in Cygnus A.

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1 Introduction

Radio galaxies are traditionally known by their radio emission, which arises from magnetised jet plasma, accelerated to large velocities in the active nucleus, and expelled up to Mpc distances. During their growth, they displace and compress the ambient gas. In the central and dominant cluster galaxies (cDGs), this gas is usually dense enough to be seen in the X-ray regime by bremsstrahlung. The Chandra observatory can now resolve these centers of galaxy clusters with unprecedented resolution. The displaced hot gas (10^7 K) has been detected in several cases (e.g. Soker et al., 2002, and references therein). An exceptional case is the Cygnus cluster with its famous FR II radio galaxy Cygnus A. This is the only nearby (redshift z=0.06) powerful jet source. In Cygnus A, the leading bow shock can be found on the X-ray image (Smith et al., 2002, also compare Chandra homepage). The identification is easy: It closely engulfs and follows the radio lobes in vicinity of the hotspots, and forms an almost spherical bubble around the radio emission. It also reproduces the armlength asymmetry. From this data, the axis ratio of the bow shock can be determined to 1.2. Comparison with the radio data gives a bow-shock-to-cocoon width of 3.8. In the symmetry plane, X-ray bright filaments are present, next to and within the radio lobe. Such excellent data demands detailed modelling. We have simulated a jet with the conditions assumed to be present in Cygnus A (sec. 2). The simulation is bipolar in order to take into account interactions of the backflows of the jets. Because it fails to reproduce the data, quantitatively, we present a parameter study in sec. 3. Finally, we present a modified jet model for Cygnus A in sec. 4 and discuss the application to comparable jet sources.

2 Bipolar 3D Simulation

Using the code Nirvana (Ziegler and Yorke, 1997), we simulated (Krause, 2002) a bipolar jet in 3D and cylindrical coordinates with the parameters of the Cygnus A jet, estimated by Carilli and Barthel (1996): beam radius $r_\mathrm{j} = 550$ pc, velocity $v_\mathrm{j} = 0.4c$, power $L_\mathrm{j} = 10^{46}$ erg/s, and external density profile $\rho(r) = 10^{-25}[1 + (r/35\mathrm{kpc})^2]^{-9/8}$ g/cm^3. The density contrast η is 6×10^{-3} at the inlet and the Mach number is $M = 10$.

A slice through the computational volume at a time of 1.6 Myr is shown in Fig. 1. Some basic features of such a jet are: Initially, the bow shock forms a spherical bubble. Then it first elongates the bubble, and after some time it produces cigar shaped extensions. The aspect ratio of the bow shock is monotonically increasing for the whole simulation. At the time shown, one jet arm is longer than the other one by $\approx 10\%$. The background is slightly asymmetrically perturbed, with the higher density on the side of the longer jet. This shows that the asymmetry is caused by the action of KHIs on the jet beam. The central part of the bow shock is pressure driven and its width turns out to scale as $t^{0.6}$, for the whole simulation time.

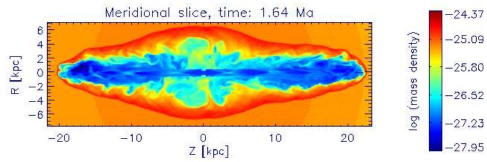

Fig. 1. Density slice for the 3D simulation. The jet is injected in the center in opposite directions.

The observed jet in Cygnus A has basically the same features as the simulated one. The bow shock is a big bubble with a cigar shaped extension on one side. The armlength asymmetry is $\approx 10\%$. But the bow-shock-to-cocoon width ≈ 1.3 and the axis ratio of the bow shock (> 3) is far-off the observed values. Hence, the assumed parameters wer not a good choice.

3 Parameter Study

In order to find out, what parameters differ and in which direction, we performed an axisymmetric study with constant background, density contrasts $\eta \in [10^{-5}; 10^{-2}]$, and Mach numbers of 3, 8, and 26 (Krause,

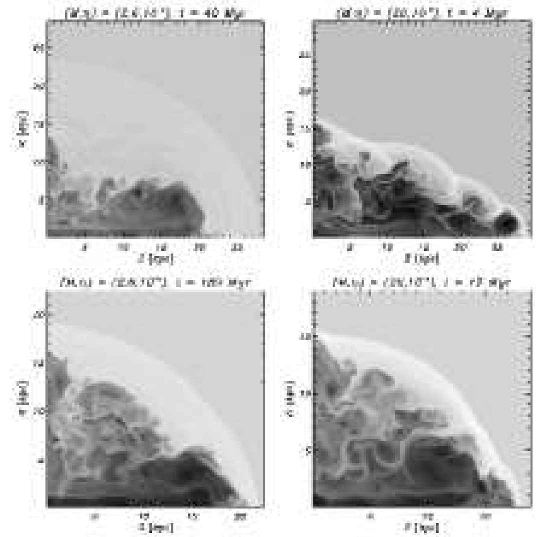

Fig. 2. Logarithmic density plots of the parameter study. Top row: $\eta = 10^{-2}$, bottom row: $\eta = 10^{-4}$. Left column: M=3, right column: M=26. Darker colour corresponds to less dense regions.

2003). Fig. 2 shows that the trend found in classical parameter studies (Norman, 1993, cocoon radius $r_c \propto M\eta^{-1/4}$) is also confirmed here: the lighter jets show fatter cocoons. However, the cocoons of the $\eta = 10^{-4}$ jets are still under-expanded, which may be the reason for the independence of r_c on M. The bow shocks are spherical at the beginning, because the pressure inside the jet bubble drives them faster than the thrust at the jet head. The relevant equation is the force balance at the bow shock, which can be transformed into the following integral equation

$$\int_0^r \mathbf{M}(r) r dr = 2 \int_0^t dt_1 \int_0^{t_1} E(t_2) dt_2 \quad (1)$$

that relates the mass $\mathbf{M}$ inside the radius r to the energy E, injected during the time t. For constant energy injection rate and constant density profile, one obtains the solution of Castor et al. (1975): $r = (5L/4\pi\rho_0)^{0.2}\, t^{0.6}$. The critical radius for the first deviation from spherical symmetry is given by: $r_1/r_\mathrm{j} = 0.5\eta^{-1/4}$which can be checked in the simulations. All the simulated jets show a high cocoon pressure, which decreases in time, as expected for a blastwave with constant energy input. The jet beam does not react by compression or expansion, but by adjusting its own pressure via oblique shock waves. The result is approximate pressure equilibrium, besides the hot spot.

4 Discussion

The 3D simulation has falsified the assumed parameters for Cygnus A. The observed cocoon and bow shock is wider than in the simulation. This points to a more extreme density contrast. It turns out from the parameter study that $\eta \approx 10^{-4}$ is needed in order to get the observed values. This agrees well with the extrapolations of Rosen et al. (1999) concerning the cocoon width. Equation 1 can be used to infer the average jet power ($L = 8 \times 10^{46}$ erg/s), and the age ($t = 27$ Myr), which agrees with estimates in the literature. The simulations have shown that the pressure has the same order of magnitude in the whole system. The external pressure in the cluster gas is (Smith et al., 2002): $p_\mathrm{ext} \approx 3 \times 10^{-10}$ erg/cm^3. The magnetic energy density in the hot spots is $u_\mathrm{mag,HS} = 9 \times 10^{-10}$ erg/cm^3 or higher (Wilson et al., 2000), assuming self-synchrotron-Compton origin of the X-ray emission. This is roughly the equipartition value. Since the magnetic field in the hot spots is probably shock-amplified, this implies a similar value of the internal energy in the jet and the cluster gas, as predicted by the above model. Given the density contrast of $\eta = 10^{-4}$ and taking into account a possibly relativistic jet (compare Scheck et al., 2002), we estimate: $\Gamma^2 h \rho_{\rm j} c^2 \approx 10^{-8}$ erg/cm^3 (Γ: bulk Lorentz factor, h: specific relativistic enthalpy, ρ_j: mass density). Consequently, the kinetic power of the jet is: $L_{\rm kin} = 2\pi r_{\rm j}^2 \rho_{\rm j} \Gamma(\Gamma h - 1)\beta c^3 = 5 \times 10^{45}(1 - 1/\Gamma h)$ erg/s. ($\beta = v_{\rm j}/c$) Since this falls short of the value derived above, the energy has to be in the magnetic power: $L_{\rm B} = r_{\rm j}^2 \Gamma^2 \beta c B^2/4 = 5 \times 10^{44}(u_{\rm mag,j}/u_{\rm mag,HS})^2 \Gamma^2$. It follows, that Γ has to be roughly 20. The mass flux in the jet is then given by: $\dot{M} = \pi r_{\rm j}^2 \rho_{\rm j} \Gamma \beta c = 3 \times 10^{-3} h^{-1} M_\odot$/yr. Appl and Camenzind (1988) estimate the mass flux needed in order to produce the observed luminosity in the Cygnus A hotspots downstream of a MHD shock: $\dot{M} = 5 \times 10^{-4} \epsilon_{\rm rel}^{-1} M_\odot$/yr ($\epsilon_{\rm rel}$: energy fraction in relativistic electrons). This does not preclude protons in the jet, and places h in the regime of a few.

The 3D simulation shows that the KHI is strongest in the symmetry plane, drawing fingers of shocked external cluster gas into the radio cocoon. We propose that some of the X-ray enhancements inside the cocoon could be due to this process. Outer X-ray enhancements may be caused by waves that the KHIs excite in the shocked cluster gas.

Some cDGs show similar features like Cygnus A. For example, the X-ray structure of 3C 317 (Blanton et al., 2001) (two elliptical rings, elongated in the same direction) can be explained as a bubble with a cigar shaped extension, seen at an inclination of 37°.

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