Three-dimensional magnetohydrodynamic simulations of the evolution of magnetic fields in Fanaroff-Riley class II radio sources

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ABSTRACT
Radio observations of Fanaroff-Riley class II sources often show correlations between the synchrotron emission and the linear-polarimetric distributions. Magnetic position vectors seem to align with the projected emission of both the radio jets and the sources’ edges. Using statistics we study such relation as well as its unknown time evolution via synthetic polarisation maps of model FR II sources formed in 3D-MHD numerical simulations of bipolar, hypersonic and weakly magnetised jets. The magnetic field is initially random with a Kolmogorov power spectrum, everywhere. We investigate the structure and evolution of magnetic fields in the sources as a function of the power of jets and the observational viewing angle. Our synthetic polarisation maps agree with observations, showing B-field vectors which are predominantly aligned with the jet axis, and show that magnetic fields inside sources are shaped by the jets’ backflow. Polarimetry is found to correlate with time, the viewing angle and the jet-to-ambient density contrast. The magnetic structure inside thin elongated sources is more uniform than inside more spherical ones. We see jets increase the magnetic energy in cocoons in proportion to the jet velocity and the cocoon width. Filaments in the synthetic emission maps suggest turbulence develops in evolved sources.

Key words: galaxies: jets – galaxies: active – intergalactic medium – methods: numerical – MHD – turbulence

1 INTRODUCTION

Centimetric wavelength observations reveal synchrotron emission from extragalactic Fanaroff-Riley Class II radio sources (Fanaroff & Riley 1974; FR IIs hereafter) and radio-loud quasars (see e.g. Bridle & Perley 1984 and references therein). Linear polarisation fractions within \( \sim 10-50\% \) are commonly seen in these objects. Polarisation maps of these sources show patchy distributions which correlate with the luminosity distribution (see Saikia & Salter 1988 for a review). Projected magnetic field vectors are predominantly parallel to both the radio jets and the boundaries of radio lobes (Alexander, Brown & Scott 1984; Bridle & Perley 1984; Leahy, Pooley & Riley 1986, 1997; Black et al. 1992; Johnson, Leahy & Garrington 1995; Hardcastle et al. 1997, 1998; Leahy et al. 1998; Gilbert et al. 2004; Mullin et al. 2006). Strong emission gradients are often followed by the vectors perpendicularly, and when multiple hotspots are observed in one of the two radio lobes, the vectors seem to follow a line that would connect the hotspots. Linear polarisation fractions of radio jets tend to be higher at the edges than at inner regions. Linear polarisation fractions of radio lobes tend to be higher at the edges than at regions both inside and between the lobes (Saikia & Salter 1988).

The direction of the magnetic field component that is in the plane of the sky is often inferred by computing the Stokes parameters on the observed signal. It is possible to do the calculations inversely in order to model the polarimetry distribution that results from given magnetic field geometries (Laing 1981; Jones 1988). Such studies indicate that magnetic fields in FR IIs seem to consist of a combination of ordered and disordered (anisotropic) fields along the jets and their vicinities, as well as a random component at the inner regions of radio lobes (Laing 1981; Bridle & Perley 1984).

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Circumferential magnetic structures are also frequently observed in the outer edge of the sources (Bridle & Perley 1984; Saikia & Salter 1988).

Based on the radio luminosity distribution observed in several FR IIs, Rees (1971), Longair, Ryle & Scheuer (1973), Blandford & Rees (1974) and Scheuer (1974) proposed the following model for the plasma dynamics in the sources. Magnetised relativistic plasma jets are launched from a central engine located inside active galactic nuclei (AGN) which are typically seen at positions that match those of the radio cores. A cavity (the cocoon, hereafter) is inflated with the jets’ plasma and a strong bow shock is driven on the ICN. Jets collide with the ambient medium at their working surfaces. Radio hotspots are seen at the leading edges of the lobes because the plasma pressure is the highest there. The plasma nearby is pushed towards the radio core and a backflow of magnetised plasma develops. Radio synchrotron lobes are thus formed, separated from the ICN by a contact discontinuity.

At kiloparsec-scales, magnetic fields in FR IIs are often modelled in energy equipartition with the synchrotron emitting ultra-relativistic electrons. Magnetic flux freezing is expected to bond field lines and radio emitting electrons dynamically, hence the jets’ backflow should play an important role in shaping magnetic fields inside cocoons (Laing 1981; Alexander, Brown & Scott 1984; Leahy & Williams 1984; Milled 1985; Saikia & Salter 1988).

The expansion of radio sources must be considered to understand their inferred magnetic structure. Evolutionary models have provided analytical expressions for the global time dependence of the volume, the pressure and the energy inside cocoons (Scheuer 1974; Falcke 1996; Begelman & Cioffi 1989; Kaiser & Alexander 1997; Krause 2004; Heinz, Reynolds & Begelman 1998). The large-scale features of the complex non-linear dynamics in such plasma cavities have been captured by numerical simulations (for reviews see Norman 1993; Ferrari 1998; Pudritz et al. 2002).

Two-dimensional axisymmetrical simulations of magnetised jets have confirmed the basic picture regarding jets (beams), lobes (cocoons) and bow shocks (e.g. Clarke, Norman & Burns 1996; Kössel, Müller & Hillebrandt 1996a, b; Lind et al. 1998, Frank et al. 1998; Stone & Harder 2000; Komissarov 1999). These simulations also show that cocoons consist of a series of vortices. These structures arise in a complex feedback loop, where pressure modulations in the cocoons interact with the beams’ shock pattern which, in turn, modifies the vortex shedding. The vortices decay in a turbulent cascade (compare section 3 in Krause & Alexander 2004). The latter process results in some degree of isotropisation of the field lines which should affect the alignment of magnetic fields and the fractional polarisation.

Further, the expansion of cocoons involves magnetic field amplification. This happens via two field line stretching processes (Matthews & Scheuer 1996). The poloidal stretching mechanism, which arises because the fluid elements in the beam located close to the beam boundary take small turns, and thus end up towards the inner part of cocoons. In contrast, the fluid elements close to the jet axis make larger turns and end up near the outer cocoon boundary. Because of the larger path length of these fluid elements, they lag behind. Hence shear amplifies the magnetic field in cocoons along the direction of the jet axis. On the other hand, the toroidal stretching process amplifies the toroidal component of magnetic fields via cocoon expansion perpendicular to the jet axis. Unless the flow structure is axisymmetric, which is an unlikely configuration for real radio sources, the toroidal magnetic field may again be sheared, and thereby converted into poloidal field. To first order, the resulting magnetic field structure is determined by both, these competing processes and the initial condition. This picture has been refined by Gaibler, Krause & Camenzind (2009) who initialised their simulation with a helical magnetic field confined to the beam. The poloidal component of these fields returns to the source along, and close to, the beam, and therefore its strength drops steeply with distance from the jet axis, $R$. The radial cocoon expansion puts work into the toroidal field which, consequently, increases linearly with $R$, as predicted by Matthews & Scheuer (1990, toroidal stretching). Hence, the magnetic energy in radio lobes could be largely due to dynamo action in the large scale jet flow, with little dependence on the conditions (set up) at the base of the beam. The literature on three-dimensional jet simulations, in contrast, has not paid much attention to these issues.

In general, one finds jet instabilities which are transparent to simulations with less degrees of freedom, e.g. jet deflection, disconnection and splash-back (see e.g. Norman 1993). Jet propagation has been studied also with relativistic MHD codes (e.g. Leismann et al. 2005; Keppens et al. 2005; Mignone et al. 2010, and references therein). These studies have not particularly focussed on polarisation properties. Relativistic jets have narrow cocoons for a given rest mass density ratio, and more stable beams. The motions in radio lobes are subrelativistic, and hence their physics should not be too much influenced by a relativistic nature of the jet.

Synthetic observations are produced using data from numerical simulations in order to compare them with observations. Matthews & Scheuer (1990) simulated the hydrodynamic advection and polarized synchrotron emission of random, passive magnetic fields in AGN jets, finding high linear polarisation fractions, of about 70%. Clarke (1993) carried out 3D simulations of the interaction of a jet and a cloud with passive uniform magnetic fields. The synthetic synchrotron emission maps of Clarke showed filaments, formed by velocity shear. Hardee, Clarke, & Rosen (1997) carried out 3D-MHD simulations of supermagnetosonic magnetised perturbed equilibrium beams, where a section of an infinitely long beam is studied, and found synthetic intensity structures similar to the ones observed in the jets of Cygnus A. More recently, Tregillis, Jones & Ryu (2004b) investigated the fractional polarisation of synthetic synchrotron observations of 3D-MHD AGN jet simulations. They found rather high fractional polarisations in regions where shock acceleration increases the emissivity, but much smaller fractional polarisation at regions where relativistic particles illuminate the volume more uniformly. In general, little attention has been given to the statistics of synthetic polarimetry and the way it relates with the properties of radio jets.

In this paper we present 3D-MHD numerical simulations of hypersonic magnetised jets as well as synthetic synchrotron and polarisation observations. In contrast to Gaibler et al. (2009) and much other work, we do not start with a regular magnetic field component within the jet, but rely entirely on the field amplification due to the dynamics of cocoons (compare above) to create structure. Regarding
analysis and the questions we address, we follow essentially Matthews & Scheuer (1990) with the important improvement that here we use a full three-dimensional magnetohydrodynamic treatment for the jet simulation.

This paper is organised as follows: in Section 2 we describe the formalism of ideal MHD and the numerical methods we use. Our implementation of the ICM, CMFs and AGN jets are also described there along with details of our calculations for the synthetic synchrotron emission and polarimetry. In Section 3 we talk about the flow structure in our model sources and analyse it in terms of energetics. Synthetic maps are then presented and compared with FR II radio observations. The results are then interpreted and analysed statistically. Section 4 is dedicated to compare AGN jets are also described there along with details of our models we use. Our implementation of the ICM, CMFs and OEDs we use. The results are then interpreted and summarise and conclude our study in Section 5 which is followed by the bibliography.

2 SIMULATIONS

We describe the dynamics of plasma in the ICM and AGN radio jets using the system of nonlinear time-dependent hyperbolic equations of ideal compressible MHD. In three dimensions and non-dimensional conservative form, these are given by:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = \rho_j \]  
\[ \frac{\partial (\rho \mathbf{V})}{\partial t} + \nabla \cdot (\rho \mathbf{V} \mathbf{V} + p \mathbf{V} + p B^2/2 - B \mathbf{B}) = \rho g + \mathbf{P}_j \]  
\[ \frac{\partial \mathbf{E}}{\partial t} + \nabla \cdot \left[ (E + p + B^2/2) \mathbf{V} - B (\mathbf{V} \cdot \mathbf{B}) \right] = \dot{E}_j \]  
\[ \frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{V} \times \mathbf{B}) = 0 \]  

where \( \rho \), \( p \), \( \mathbf{V} \) and \( \mathbf{B} \) are the plasma density, thermal pressure, flow velocity and magnetic fields, respectively. In (1), (2) and (3) source terms are used to implement jets by injecting mass, \( \dot{\rho}_j \), momentum, \( \dot{P}_j \), and kinetic energy, \( \dot{E}_j \) (see Section 2.2), as well as a Newtonian gravitational acceleration, \( g \), to keep the plasma in magneto-hydrostatic equilibrium (see Section 2.1.1).

We solve the above equations in three dimensions using the numerical code Flash 3.1 (Fryxell et al. 2000). Flash’s new multidimensional unsplit constrained transport solver is employed to maintain the divergence of magnetic fields down to \( \leq 10^{-12} \) (Lee & Deane 2008). A diffusive HLLC solver (Batten et al. 1997) prevents spurious low pressure and density values from appearing in the grid. We use a Courant-Friedrichs-Lewy parameter of 0.25 and periodic boundary conditions in all the domain’s faces. These boundary conditions prevent numerical noise from polluting the turbulent magnetic spectrum in the grid (Section 2.1.2). Our computational domain is a cube with edges \( |x| \leq 1/2 \), in computational units, and has a uniform grid with 200 cells. This represents a volume of 200 kpc\(^3\) meant to simulate the core of a cluster.

We carried out five jet simulations (see Table 1) designed to experiment with the power of jets in terms of their velocities and densities. Computations ran for approximately 12 hours on 64 processors at the CamGrid\(^1\) cluster of the University of Cambridge, and the production runs executed for about 4 hours (using 64 processors) at the Darwin\(^2\) supercomputer of the University of Cambridge HPC facility.

2.1 Initial conditions

2.1.1 The ICM

The cluster plasma is implemented using an equation of state of an ideal monoatomic gas, with a ratio of specific heats \( \gamma = 5/3 \), a constant sound speed \( (c_s^2 = \gamma p_0/\rho = 1) \) throughout the domain and a density following a King profile (King 1972):

\[ \rho_{\text{ICM}}(r) = \frac{\rho_c}{(1 + (r/r_c)^2)^{3/2}}, \]

where the central density, \( \rho_c \), the central radius, \( r_c \), and \( \beta \) take the values of 1, 0.8 and 2/3, respectively.

To keep the magnetised gas in magneto-hydrostatic equilibrium we implement a radial acceleration source term \( g \) to equation (2), and take the balance between this term and the total plasma pressure \( p_0 + B^2/2 \). In the radial direction this term takes the form:

\[ g_r = - \frac{2 c_s^2}{\gamma r^2} \left( 1 + \frac{1}{\beta_m} \right), \]

where \( \beta_m \) is the ratio of thermal pressure to magnetic pressure.

2.1.2 Cluster magnetic field

The magnetic field within the cluster is set up as an isotropic random field with a power law energy spectrum. Following Tribble (1991) and Murgia et al. (2004) we generate a cubic grid in Fourier space, with 200 cells. For each of these, we define three components of a vector potential which takes the form \( \mathbf{A}(k) = A(k) e^{i \theta(k)} \), where \( k \) is the frequency vector \( (k_x^2 + k_y^2 + k_z^2) \). \( i \) is the unitary complex number, while \( A \) and \( \theta \) are the vector amplitudes and phases, respectively. We draw \( \theta(k) \) from a uniform random distribution within 0 and \( 2\pi \), and \( A(k) \) is also randomly distributed but has a Rayleigh probability distribution

\[ P(A, \theta) dA d\theta = \frac{A}{2\pi |A_k|^2} \exp \left( -\frac{A^2}{2|A_k|^2} \right) dA d\theta, \]

where we choose the power law Ansatz

\[ |A_k|^2 \propto k^{-\zeta}, \]

for a given slope \( \zeta \).

We transform to real space by taking the inverse fast Fourier Transform (Press et al. 1992) of \( \mathbf{A}(k) \). The resulting magnetic vector potential, \( \mathbf{A}(x) \), is multiplied by the plasma density radial profile (3). This product implements magnetic flux freezing by generating fields, the strength of which follows the plasma density, and pressure, profile. The components of the vector potential are then read and mapped

\(^1\) http://www.escience.cam.ac.uk/projects/camgrid/  
\(^2\) http://www.hpc.cam.ac.uk/darwin.html
into the staggered-grid cell interfaces of Flash3.1 and the curl of this vector is then calculated to give the magnetic field. Finally, we normalise the resulting field so that the ICM’s thermal pressure is approximately ten times larger than its magnetic pressure ($\beta_\text{ICM} = p_\text{th}/(B^2/2) \sim 10$) everywhere in the grid, which is a reasonable value in this context (Carilli & Taylor 2002).

This procedure yields solenoidal magnetic fields tangled at scales of order our computational resolution and characterized by spatial variations following a magnetic power spectrum with a power law of the form

$$|B|^2 \propto k^{-\zeta+2} = k^{-\eta},$$

where we choose a Kolmogorov three-dimensional turbulent slope $\zeta = -11/3$, based on the work of Vogt & Enßlin (2004, 2005) and Guidetti et al. (2008). We use the same realisation for all our runs. We note that the Fourier method implicitly imposes maximum and minimum scale on the field.

We let this plasma relax for one crossing time before injecting the jets.

### 2.2 Jets

By implementing source terms to equations (1), (2) and (3) we inject mass, $x$-momentum and kinetic energy to the central grid cells that are within a control cylinder of radius $r_j$ and height $h_j$, resolved by 3 and 8 cells, respectively. Inside this “nozzle” we update the plasma density and $x$-velocity via constant source terms $\rho_j$ and $\dot{v}_j$. Jets are continuously injected until they reach the computational boundaries and then the simulations are stopped. Plasma pressure in the nozzle, $p_j$, takes the constant value of the central ambient pressure (i.e. $\rho_c/\gamma$). The jet density is computed with $\rho_j = \eta \rho_c$, where the parameter $\eta$ takes the (low) values given in Table 1. We assume an ideal gas equation of state with $\gamma = 5/3$ for the jet material. The light densities of our jets are motivated by the work of Alexander & Pooley (1996) and Krause (2003), and their high Mach numbers are based on the observed jets sidedness associated with Doppler beaming, suggesting that FR II sources are at least close to relativistic up to scales of order 100 kpc (Mullin & Hardcastle 2009). The Mach numbers of our jets with respect to the sound speed in the ambient gas are 40, 80 and 130 which correspond to velocities close to $66 \times 10^3$, $133 \times 10^3$ and $216 \times 10^3$ km s$^{-1}$, respectively. The Mach numbers of the jets with respect to the sound speed in the beam material are 2.5, 5.7, 5.11.3 and 8.2, as they appear in Table 1. We extend the implementation of Omma et al. (2004) to simulate bipolar magnetised jets. The launch and collimation of the jets are assumed to occur in the AGN “central engine” located at sub-resolution scales.

The initial jet magnetic fields are kept from the initialisation of the ambient medium, and no magnetic field term is applied. It therefore has a random topology, an average $\beta_{\text{jet}} \sim 10$ and, given the assumed power spectrum (Section 2.1.2), it is fairly uniform at scales $\sim r_j$. We note, however, there is no reason to believe the magnetic fields in FR II radio jets are related to the CMFs near the AGN; jet fields are expected to be advected up the beam from the central engine. Our choice of initial jet magnetic fields is based on the fact they seem to be weak at kiloparsec-scales and to have a random component (Section 1). This is the case of the central fields in our model.

As our jets propagate, their magnetic fields are deformed by shear. The time averaged average beam $\beta_{\text{jet}}$ is of about 50. The power of jets is the sum of thermal and kinetic power terms:

$$L_j = \int \left( \frac{1}{2} \eta \rho_c \dot{v}_j \right)^2 \, v_x \, dA + \int \left( \frac{\gamma \rho_c}{\gamma - 1} \right) \, v_x \, dA,$$

which takes the following form at the grid

$$L_j = \frac{1}{2} \eta \rho_c (\pi r_j^2) \dot{v}_j^2 + \frac{\gamma}{\gamma - 1} \, p_j (\pi r_j^2) \dot{v}_j.$$  

#### 2.2.1 Cocoon contact surface

We use a passive incompressible tracer, $\tau(x, t)$, which is injected with the jet plasma to distinguish it from that of the ambient medium. When jet injection starts, $\tau(x, t_{\text{jet}} = 0)$ takes the values of 0.99 and $1 \times 10^{-10}$ at the nozzle and at the ICM, respectively. The tracer is then advected with the jet gas and takes values within $1 \times 10^{-10}$ to 0.99. A comparison of the distributions of $\tau$ and $\rho$ allows us to identify the contact surface of the cocoon with an accuracy up to 4 computational cells.

#### 2.3 Synthetic radio maps

Our simulations produce three-dimensional data cubes with information about the distribution of the magnetised gas in our model sources at different times during their expansion. Synthetic synchrotron emission and polarimetry are computed under the assumption that the radiation is linearly polarized. Beaming and light-travel effects are assumed to be negligible. Synthetic observations are produced at viewing angles, $\theta_v$, of 30, 60 and 90 degrees measured from the jet axis to the line of sight (thus jets are in the plane of the sky when $\theta_v = 90^\circ$). Given a viewing angle and a simulation timestep, $t$, Stokes parameters are (i) calculated for every computational cell inside the source, using the magnetic field components in the plane of the sky, $\mathbf{B}(x, t)$, (ii) integrated through the source, along the line of sight, $Z(t)$. Mathematically,
3D-MHD simulations of evolving magnetic fields in FR II radio sources

Figure 1. Two dimensional cuts (z = 0) of the density (top row), the pressure (middle row) and the magnetic field strength (bottom row) distributions. The Mach number and density of the runs are given on the top of each column. Colour scales are logarithmic and show variables in corresponding computational units. We see a clear relation between the intrinsic structure of sources and the resultant field structure in the synthetic polarisation maps (Figures 4–8).

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Figure 2. Two dimensional cuts ($z = 0$) of the magnetic fields for the Mach 80 jets (see Table 1). Colour scales are linear and show variables in corresponding computational units.

\[ I(x_{\perp}, t) = \frac{1}{4} \int_0^l \delta(\tau(x, t)) p_c(x, t) \left[ B'_x(x, t)^2 + B'_y(x, t)^2 \right] d\tau_\parallel(t), \]

\[ Q(x_{\perp}, t) = \frac{0.75}{4} \int_0^l \delta(\tau(x, t)) p_c(x, t) \left[ B'_x(x, t)^2 - B'_y(x, t)^2 \right] d\tau_\parallel(t), \]

\[ U(x_{\perp}, t) = \frac{0.75}{4} \int_0^l \delta(\tau(x, t)) p_c(x, t) 2 B'_x(x, t) B'_y(x, t) d\tau_\parallel(t), \]

where

\[ \delta(\tau) = \begin{cases} 
1 & \text{for } \tau(x, t) \in [0.5, .99] \text{ (cocoon)}; \\
0 & \text{for } \tau(x, t) \in [1 \times 10^{-10}, 0.5] \text{ (ambient)}. 
\end{cases} \]
and \( x, p_c(x, t) \) and \( I \) represent the coordinates in the plane of the sky, the distribution of the cocoon pressure and the total intensity of the radiation, respectively. We note that [12] are valid for a synchrotron emission spectral index \( \alpha = 1 \), yet the degree of polarisation we predict does not vary too much with \( \alpha \) [Laing 1980]. The factor of 0.75 in the expression of \( Q \) and \( U \) in [12] accounts for the maximum degree of linear polarisation for a uniform magnetic field and a power-law electron energy distribution. We model the density distribution of synchrotron emitting electrons via the factor \( \tau(x, t) p_c(x, t) \) in [12]. We do not follow any explicit energy gain or loss processes such as synchrotron cooling or shock acceleration (i.e. the background plasma pressure is proportional to the constant factor in the energy distribution of relativistic electrons). A detailed treatment of the electron distribution is beyond the scope of this paper. We note that we have also tried a constant density of radiating electrons, which did not significantly change the results. The polarisation angle of the magnetic vectors, \( \chi_{B} \), and the degree of linear polarisation (= fractional polarisation), \( p \), are given by

\[
\chi_{B} = \frac{1}{2} \arctan(U/Q) + \frac{\pi}{2}, \quad p = \frac{\sqrt{U^2 + Q^2}}{I}.
\]

3 RESULTS AND ANALYSIS

Synthetic polarisation and emission maps are presented in pairs characterized by the jet velocity (same as the external Mach number), the density contrast \( \eta \), the viewing angle \( \theta_{v} \), and the time that jets have been active, \( t_{jet} \). Polarisation maps have a constant vector density of 0.5 cells\(^{-2}\).

3.1 Flow structure

The hydrodynamic flow structure of our simulations is very similar to what is generally found in the literature (compare section [1] above, Figure [1]). The hypersonic jets flow straight for a certain distance (2D-phase). Then three-dimensional instabilities develop, more clearly in the lighter jet runs, and the jet head oscillates around the jet axis, consistently with Scheuer’s dentist drill (3D-phase). Cocoons are wider for lower jet density and faster jets, as expected. The relatively heavier jets (\( \eta = 2 \times 10^{-3} \)) propagate faster in the axial direction, and backflows in their cocoons are much less turbulent than in their relatively lighter (\( \eta = 4 \times 10^{-3} \)) counterparts.

The evolution of cocoon magnetic fields is driven by the following dynamics. The field is initially random inside the jet injection volume. The injected momentum stretches field lines along the jet direction. This puts energy into the axial field, which is therefore amplified. The other field components are simply advected out of the injection volume, and their field strength drops with time, within the injection volume and the beam. This process results in a poloidally dominated magnetic field, similar to the setup in Gaibler et al. (2009), yet with some important differences: First, the field in the axial direction is patchy (compare Figure [2] for this and other details of the magnetic field), i.e. adjacent parts of the beam have the field parallel and anti-parallel to the flow direction. Second, for a given plane perpendicular to the flow vector, the field may in principle also be patchy, i.e. there is not necessarily one dominant toroidal field loop, but possibly two or more field loops across a section of the jet. However, the fact that the power spectrum used for the initial field setup strongly favours larger scales, still produces a predominantly toroidal configuration for the magnetic field perpendicular to the jet axis.

As Gaibler et al. (2009) do, we find that the axial field lines return to the injection region very close to the jet. In our case this may even happen inside the beam, since any beam cross section may in general contain axial field patches of opposing directions. In the presence of a backflow, this requires field line reconnection, which should be easily possible in the jet head on numerical grounds due the complex flow pattern in this region. This seems to suggest that the general structure of the poloidal magnetic field does at least not very much depend on the initial conditions. The reason is that the elongation of the beam stretches the axial field lines and therefore amplifies the axial field. To have the field lines going out in the beam and returning close to it or even within is the configuration which requires the least amount of energy, and is therefore chosen by the system.

Gaibler et al. (2009) find the toroidal part of the field, which cannot be lost to other field components via turbulence due to the axisymmetry condition in their study, increases linearly with distance from the jet axis. This may be easily understood from the induction equation. The physical reason is the work done by the expanding cocoon on the toroidal field component is stored in that part of the magnetic field. We do not observe such a linear increase in the toroidal field in our 3D simulations directly, but we expect this process also to be at work. Since it is related to the cocoon expansion, we expect more magnetic energy to be created by fatter cocoons, i.e. for lower jet density (most important for the cocoon width), and higher jet velocity, which is also found by Gaibler et al. (2009). They also show that this process is able to enhance the total magnetic energy in the jet by a factor of a few (see their Figure 20). For our simulations, therefore, we expect a noticeable increase in the magnetic energy during the simulation time: the fatter the cocoons the higher the energy rise. Figure 3 shows this expectation is exactly what we find: Here we plot...
Figure 4. Synthetic observations of the source with $\eta = 0.004$ and Mach = 40. Left: polarisation maps. Vectors follow $\chi_B$ and their length is given by $p$. Vectors are superimposed on linear contours of $I/\langle I \rangle$. Right: logarithmic grayscale maps of $I/\langle I \rangle$. 
Figure 5. Synthetic observations of the source with $\eta = 0.004$ and Mach = 80. Left: polarisation maps. Vectors follow $\chi_B$ and their length is given by $p$. Vectors are superimposed on linear contours of $I/\langle I \rangle$. Right: logarithmic grayscale maps of $I/\langle I \rangle$. 

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Figure 6. Synthetic observations of the source with $\eta = 0.004$ and Mach = 130. Left: polarisation maps. Vectors follow $\chi_B$ and their length is given by $p$. Vectors are superimposed on linear contours of $I/\langle I \rangle$. Right: logarithmic grayscale maps of $I/\langle I \rangle$. 

(a) Time evolution at $\theta_v = 90^\circ$. From top to bottom $t_{\text{jet}} = \{1.9, 3.3, 4.7\}$ Myr.

(b) Emission at $t_{\text{jet}} = 4.7$ Myr as a function of the viewing angle; $\theta_v = 60^\circ$ (top) and $\theta_v = 30^\circ$ (bottom).
Figure 7. Synthetic observations of the source with $\eta = 0.02$ and $\text{Mach} = 40$. Left: polarisation maps. Vectors follow $\chi_B$ and their length is given by $p$. Vectors are superimposed on linear contours of $I/\langle I \rangle$. Right: logarithmic grayscale maps of $I/\langle I \rangle$. 

(a) Time evolution at $\theta_v = 90^\circ$. From top to bottom $t_{\text{jet}} = \{4.7, 5.9, 8.3\}$ Myr.
Figure 8. Synthetic observations of the source with $\eta = 0.02$ and Mach = 80. Left: polarisation maps. Vectors follow $\chi_B$ and their length is given by $p$. Vectors are superimposed on linear contours of $I/\langle I \rangle$. Right: logarithmic grayscale maps of $I/\langle I \rangle$.  

(a) Time evolution at $\theta_\nu = 90^\circ$. From top to bottom $t_{\text{jet}} = \{1.8, 3.6, 4.4\}$ Myr.

(b) Emission at $t_{\text{jet}} = 4.4$ Myr as a function of the viewing angle; $\theta_\nu = 60^\circ$ (top) and $\theta_\nu = 30^\circ$ (bottom).

175 \%, B vectors

Contours at:
0.50, 6.02, 11.54, 17.06, 22.58, 28.10, 33.62, 39.14, 39.14, 44.66, 50.18, 55.70, 61.22.
the magnetic energy in both the cocoon and beam over the source size for all runs. The curves are indeed strictly ordered according to cocoon width. All the lighter jets have more magnetic energy than any of the light ones. Among jets with a given density, the faster ones have more magnetic energy. Therefore, the underlying reason for the increase of the magnetic energy is the increase of the toroidal component due to the cocoon expansion, just as in Gaibler et al. (2009). There is another detail that confirms this finding: As described above, we find the usual 2D and 3D-phases for our jet simulations. The described amplification mechanism is very different in each phase. During the 2D-phase, field loops released in the jet head expand axisymmetrically, and substantial work is required to stretch them. Energy from this work is later found in the magnetic field. In contrast, during the 3D-phase the dentist’s drill moves the jet head away from the axis in different directions. Field loops therefore do not have to expand to reach large distances from the axis. They may keep their size, and get pushed into different corners of the cocoon at different times. Hence, once cocoon inflation reaches and goes through the 3D-phase, almost no work is put into the field anymore. We believe this mechanism causes the turnover in the magnetic energy seen in Figure 3. This turnover is visible for all the lighter jets at the comparable source size. The light jets, on the other hand, do not show much of an amplification in the first place, and also remain quite straight, i.e. essentially in the 2D-phase up to the end of the simulations. As expected, we do not find the turnover there. We note that a similar turnover is not found in the axisymmetric simulations by Gaibler et al. (2009) either, which is of course expected if it is linked to the 3D-phase.

Why do we not see a linear increase with distance from the jet axis in the toroidal field like Gaibler et al. (2009)? Because of the 3D nature of the cocoon turbulence in our simulations. While axisymmetric turbulence can only stretch and compress a given toroidal field, 3D-turbulence may also turn toroidal field into poloidal one. The result is a turbulent cocoon field, with no geometrical similarity to the 2D-result.

We see a strong axial field along the edge of the cocoons (see Figure 2). This is due to velocity shear in this region (Section 3) where the time average backflow speeds with respect to the ambient medium are about $5 \times 10^3$, $5 \times 10^3$, $28 \times 10^3$, $22 \times 10^3$ and $27 \times 10^3$ km s$^{-1}$, for the sources as they appear in Table 1.

In the shocked ambient gas, on the other hand, magnetic fields are first compressed in the bow shock, and then reduced again due to adiabatic expansion of the gas, as it leaves the shock towards the cocoon. The effects of cocoon expansion on CMFs will be investigated in a sequel paper (Huarte-Espinosa, Krause, & Alexander 2011b, in prep.).

The flow structure in our simulated radio sources is dominated by large scale motions, namely the toroidal and poloidal stretching mechanisms we have discussed in this paper. We cannot claim to represent the turbulence in our simulated cocoons well, because the resolution is too poor. Higher resolution should add additional small scale structure, unless prevented by a sufficiently strong magnetic field (compare e.g. Krause & Camenzind 2001). Yet, also turbulence is expected to have most power on large scales. Therefore, while higher resolution studies will still be useful, we would expect the results discussed in this paper to hold.

### 3.2 Synthetic radio maps

In Figures 4, 6, 7 and 8 we present synthetic radio and polarisation angle maps of four of our simulated FR II radio sources (all but the lighter-relativistic one) for three different snapshot times. These maps essentially reflect the field structure discussed above. The emission is dominated by filaments, hotspots and sometimes jets are seen. This is similar to what has been found in earlier studies, as detailed in the Introduction. The jet head region is more prominent at earlier times and for higher jet density. Our lighter jets feature more diffuse jet heads reminiscent of the shock web complex, described by Tregillis, Jones, & Ryu (2001). Our polarisation angle maps are all dominated by larger patches. This is due to the fact that the cocoon dynamics is dominated by large vortices, about the cocoon radius in diameter. The backlight in our $\eta = 0.02$ jets remains quite smooth and, consequently, the polarisation vectors are even more parallel to the jet axis than they are in the lighter $\eta$ sources. Generally, we find an almost one-to-one correspondence between the flow field and the polarisation vectors, as expected.

In addition, in panel (b) of Figures 4, 6, 7 and 8 we show synthetic radio and polarisation angle maps at different viewing angles. We consistently see that at small angles the axial field component gets smaller due to the projection effect, while other field components become relatively more prominent.

The patchy distributions in our polarisation maps are in good agreement with typical observations of FR II sources and radio-loud quasars (see e.g. Bridle & Perley 1984; Saikia & Salter 1988; Gilbert et al. 2004; Mullin et al. 2006). Along the projected direction of jets we see that $|\chi_B|<20^\circ$, which are smaller angles than elsewhere inside the cocoon. For $\eta = 0.02$, $|\chi_B|$ increases progressively along the vertical direction, from the jet axis to the edge of sources (Figures 7 and 8). This is because in these simulations cocoons are narrow, and therefore the beam contributes significantly to the emission, which is not the case in most of the observed sources. In contrast, for $\eta = 0.004$, $|\chi_B|$ shows weak trends along the vertical direction. The outermost vectors in all the maps are commonly tangent to the dimmest emission contours. This is similar to observations, but is of course influenced by numerical problems at the contact surface, as outlined above.

Polarisation degrees within 37–51 % are found inside cocoons, but higher, up to ~63%, both at the edge of sources and at the position of jets. We often see uniform patches with very similar values of $|\chi_B|$ and $p$ at the position of bright emission shocks. The vectors frequently follow strong intensity gradients perpendicularly and have $p \geq 50\%$. Regions of non-uniform $|\chi_B|$, on the other hand, are frequently located between emission shocks (see e.g. Figure 4). These correlations are in good agreement with observations (e.g. see H" ogbom 1974, Laing 1981, Bridle & Perley 1984, Saikia & Salter 1988, Hardcastle et al. 1995, Leahy et al. 1995, Gilbert et al. 2004) and with models of plasma compression and shear (e.g. Laing 1981, Miles 1983).

Our synthetic emission maps often show hotspots at the location of the jets’ working surfaces as well as filaments in the radio lobes. Radio hotspots and filaments are often seen in well resolved FR II sources (e.g. Cygnus A, Perley et al. 1984).
We see the backflow of the (anti-parallel) jets collide and form sheets near the cocoon equatorial plane (the one normal to the jets and containing the central engine). There, our polarisation maps show B-vectors with $|\chi_B| > \pi/4$ above and below the centre of Figures 4–8 (left column). We found instances of such polarisation angle distributions in the observations of 3C 34, 3C 336 and 3C 341 (Johnson, Leahy, & Garrington 1995; Mullin et al. 2006 and Gilbert et al. 2004, respectively).

At the end of the simulations we see laminar flows in the cocoons and also that Rayleigh-Taylor and Kelvin-Helmholtz instabilities are growing at the contact surface (Figure 1). Such flows form tube-like structures or filaments, respectively.

3.3 Polarimetry and statistics.

In order to analyse our synthetic observations we have produced histograms of the polarisation angle and the degree of linear polarisation; see Figures 10 and 11, respectively. In what follows we will see that these distributions show a clear correlation with the viewing angle, the jet-to-ambient density contrast and time too, but only a weak dependence on the jet velocity.

3.3.1 The role of the viewing angle.

The polarisation angle histograms are similar for all runs at $\theta_v = 90^\circ$: They are all peaked towards zero degree, corresponding to the jet direction. The more isotropic distribution at lower viewing angle is consistent with cocoon turbulence. We see only the distribution of the heavier jets remains peaked at a viewing angle of $60^\circ$, because of the weaker cocoon turbulence in these sources, relative to the ones with lighter jets. This confirms the magnetic field structure is determined by the relative importance of turbulence as well as the amplification of the axial field due to the backflow in cocoons.

For $\theta_v = 30^\circ$, $60^\circ$ and $90^\circ$, the mean value of $|\chi_B(\eta = 0.004)|$ is generally larger than that of $|\chi_B(\eta = 0.02)|$ (see Section 3.3.2 below). The dispersion of the polarisation angle seems to follow this trend as well. The differences are pronounced for viewing angles of 60 and 90 degrees and related to the size of the data sample, i.e. the cocoons’ volume, which is inversely proportional to $\eta$ in a non-linear way (Section 5.1). Polarisation angle histograms at $\theta_v = 30^\circ$ show both the flattest gradients and the least number of vectors amongst all histograms, and their distribution does not show a Gaussian functional form.

As the viewing angle increases we find the mean polarisation angle, $\langle |\chi_B| \rangle$, decreases non-linearly (see Figure 10), (panel b, Figures 8&). On average, $|\chi_B|$ diminishes for about $9^\circ$ for viewing angles from 30 to 60 degrees, and about $4^\circ$ for viewing angles from 60 to 90 degrees. Cocoons have geometries that resemble prolate spheroids and thus magnetic fields inside them should relax easier along the jet axis than towards the equator. However, to produce the synthetic maps we follow two steps: (i) rotate the sources anticlockwise, perpendicularly to the jets, and (ii) project them onto the plane of the sky. Hence only the magnetic component along the jet axis (the horizontal one in the maps) is affected in this process and grows in proportion to $\cos(\theta_v)$.

The dependence of the degree of linear polarisation on the viewing angle is relatively modest and particularly evident for $\eta = 0.02$ (Figure 11). We see $\langle p \rangle$ increases about 7% from $\theta_v = 30^\circ$ to $\theta_v = 60^\circ$, and also about ~3% from $\theta_v = 60^\circ$ to $\theta_v = 90^\circ$. Hereafter, $\langle p \rangle$ represents the arithmetic mean of $p$. For all $\eta$, the number of pixels in the polarisation degree histograms consistently scales up with the viewing angle, in relation to the projected area of cocoons.

3.3.2 The role of the density contrast.

The jet-to-ambient density contrast is well known to be important for the evolution of cavities formed by astrophysical jets (see e.g. Krause 2003). Our synthetic maps show the density contrast also plays an important role on the radio source polarimetry. In general the projected area of sources is inversely proportional to $\eta$ in a non-linear way. Thus we see less magnetic fields in polarisation measurements with $\eta = 0.02$ than, 0.004.

Given a timestep and a viewing angle, we find the mean polarisation degree is typically $\sim 10^\circ$ smaller for $\eta = 0.02$ than for $\eta = 0.004$. We see the spatial distribution of the polarisation angle is more uniform for $\eta = 0.02$ than for the lighter case. e.g. gradients greater than about $10^\circ$ per computational cell ($10^\circ$/kpc) are less frequent in Figure 11 (left column) than in Figure 11 corresponding to $\eta = 0.02$ and 0.004, respectively.

The statistical behaviour of the polarisation degree is very different. Given a timestep and a viewing angle, we frequently find higher values of the mean polarisation degree for $\eta = 0.02$ than for the lighter case. On average, $\langle p \rangle (\eta = 0.02) \sim 47$%, while $\langle p \rangle (\eta = 0.004) \sim 42$%. Moreover, the polarisation degree histograms follow Gaussian-like distributions. The mean polarisation degree at large viewing angles increases with time for the heavier jets, indicating that axial field line stretching gets even more important with time. Conversely, it decreases with time for the lighter jets, which shows that turbulence gets even more important with time for the lighter jets. The polarisation degree of the lighter jets does not depend on the viewing angle.

3.3.3 Polarimetry evolution.

The main features of the polarisation angle histograms seem to be shaped during the early expansion phase of the model sources, particularly for viewing angles of 60 and 90 degrees. Here, magnetic fields tend to align with the jet axis ($\chi_B = 0^\circ$) as sources expand (panel a, Figures 8&). The considered histograms decline steeply up to about $20^\circ$ to $40^\circ$, and remain roughly constant for higher $\chi_B$. The constant part is at a very similar level for all viewing angles of a given simulation. These findings correspond to the effects of
isotropic turbulence, in combination with the stretching of field lines in cocoons, predominantly along the jet direction.

The fractional polarisation evolves quite differently. At the first timestep (Figure 11, black profiles), we see that the $p$ histograms are fairly similar and show a linear relation, rising monotonically towards larger $p$. As the cocoons with $\eta = 0.004$ grow, the profiles evolve into a peaked distribution with a broad peak between about $p = 0.2$ and 0.5. In contrast, the profiles for $(\eta = 0.02, \theta_c > 60^\circ)$ always peak at $p > 0.5$. The fractional polarisation tells us about two things: (1) the degree of alignment of the field vectors that contribute to a given line of sight, and (2) the number of pixels long that line (assuming their contribution is different from each other). Hence we see the polarisation generally decreasing for $\theta = 30^\circ$. In cocoons where $\eta = 0.004$ we see a stronger $p$ decline at early times than later on. This occurs because their expansion slows down at late times, as these sources approach pressure equilibrium with the ambient medium. In cocoons where $\eta = 0.02$, on the other hand, we see a slow sideways growth and thus $p$ drops very slowly. Moreover, we see higher polarisation for larger $\eta$, again reflecting that high density jets have more ordered magnetic fields and blow thinner cocoons.

We note that an additional set of synthetic polarisation maps (not shown) was produced assuming a spatially uniform distribution of synchrotron emitting electrons [i.e. $p_c(x, t) = 1$ in (12), for all $x$ and $t$]. The polarimetric distribution of such maps was found to be very similar to the ones discussed in this section of the paper. Our results are not, therefore, sensitive to details of the electron distribution.

Radio source polarimetry is related with the study of cluster magnetic fields because they induce Faraday rotation and depolarisation on the radio source emission [Pacholczyk 1968, Burn 1969]. Faraday rotation maps contain information about the ICM’s magnetic structure (for a review see Carilli & Taylor 2002). In a sequel paper (Huarte-Espinosa, Krause, & Alexander 2011b, in prep.) we will investigate the evolution of cluster magnetic fields using statistical analysis on synthetic RM observations which are produced using the expanding model sources we present here.

4 DISCUSSION

About a handful of studies on synthetic synchrotron emission and polarimetry of extragalactic radio sources exist in the literature. We are not aware of any study that uses magnetic fields evolved in a magnetohydrodynamic simulation self-consistently with the jet, as presented here. Jones (1988) modeled relativistic jets with a turbulent magnetic field ansatz, advected with the flow velocity of the jet, to study the relation between linear and circular polarisation. Though we start from a similarly turbulent field in our initial injection region, we get about 50 per cent linear fractional polarisation. Hence, we see the polarisation generally decreasing for $\theta = 30^\circ$. In cocoons where $\eta = 0.004$ we see a stronger $p$ decline at early times than later on.

We confirm almost all of their results regarding the magnetic field structure: Matthews & Scheuer discuss in detail the toroidal and the poloidal stretching mechanism. As argued above, we believe the toroidal stretching mechanism is mainly responsible for the magnetic energy increase in co-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure9.png}
\caption{Synthetic emission filaments in the right lobe of the source with $\eta = 0.004$ and Mach = 40, at $t_{\text{jet}} = 14.1$ Myr. The structure at the centre of the figures gets shorter and dimmer as the viewing angle decreases from 90 to 30 degrees, from left to right, suggesting a tube-like geometry for the feature in question.}
\end{figure}
coons. We do not observe a dominant toroidal field directly because non-axisymmetric shear converts this component to poloidal field. We generally see a predominantly axial field component in cocoons, consistent with their poloidal stretching mechanism. In contrast to them, we also find axially stretched and amplified magnetic fields in the beams.

As Matthews & Scheuer (1990) do, we find field line stretching along the contact surface that separates cocoons from the ambient medium. In a resolution study they show...
Figure 11. Histograms of the linear polarisation degree. Panels are arranged as in Figure 10.
that the extent of that region gets smaller at higher resolution, but the field strength increases due to the increased shear. They also address synchrotron losses in the energy distribution of relativistic electrons. Due to such losses, they find that the aforementioned shear layer is very weak in synthetic radio maps. In our maps these features appear as edge enhancements and are likely a numerical artifact because our treatment does follow synchrotron losses. In reality, the two fluids may slip easily and the shear layer may be insignificant. This depends on the magnetic viscosity of the plasma and is beyond the scope of this discussion.

Moreover, as we do, Matthews & Scheuer (1990) find filaments in the synthetic emission images, but they report close to maximum fractional polarisation. We find lower, more realistic, fractional polarisation values in our simulations, especially for the lighter jets. The main reason for this difference is the breaking of axisymmetry: This allows for 3D turbulence in cocoons and for different directions of magnetic field vectors along the azimuthal direction. Yet, we also see fractional polarisation values in the cocoon body, far away from the beams and the edges, which are still somewhat high. This might be a resolution issue: the magnetic field energy spectrum is close to Kolmogorov, which we have checked for the final snapshots of all our runs. Therefore, dominant structures are the large scale ones, which we should be able to capture. However, the roughly 50 cells we have over the fatter cocoons might still be too little to capture some important small scale structure that could reduce the fractional polarisation. Our simulations show the fractional polarisation is very similar for different jet velocities. Also, as Matthews & Scheuer (1990) have already noted, cocoon magnetic fields are largely independent of the initial conditions prescribed at the base of the beams. It is therefore unlikely that there is something fundamental to the cocoon structure that we miss. Another reason for low fractional polarisation might be that our jet densities may still be too high. We find the cocoon width, which is mainly regulated by the jet density, is an important factor for the polarimetry. Observed cocoons are usually wider relative to the beam than the ones we produce here. This fact indicates lower jet densities in the observed radio sources (Alexander & Poole 1993; Krause 2003). Hence, low fractional polarisation might be yet another consequence of jets being very light compared to their surroundings. Finally, Matthews & Scheuer (1990) found small regions where field amplification and therefore synchrotron cooling became very significant in their simulations. In our 3DMHD simulations we see filaments in the cocoons (Figures 4-8, right column) and that magnetic fields there are about an order of magnitude stronger than the mean field. Thus we confirm the findings of Matthews & Scheuer (1990).

Tregillis, Jones, & Ryu (2001) carried out 3D-MHD simulations of a jet with $\eta = 0.01$, Mach=80 and a helical magnetic field, the axial part of which extended throughout the computational domain. These authors studied the diffusive shock acceleration and transport of synchrotron relativistic electrons. We do not follow such processes. Then, Tregillis, Jones, & Ryu (2004) produced detailed synthetic observations of both the synchrotron and the X-ray – due Compton scatter from CMB photons. They emphasise that along the lines of sight that pass through strong shocks, most of the emission may come from regions close to the shock, and thus have close to maximum fractional polarisation values. We might miss some of such regions due to the limitations of our simple model for the distribution of relativistic electrons. However, the emission from the bulk of cocoons cannot be dominated by such features, as the fractional polarisation we predict for such regions is too high (compare above). This would mean that real radio lobes are relatively uniformly illuminated by relativistic electrons and are not dominated by relatively few isolated shock features.

5 SUMMARY AND CONCLUSIONS

We carried out 3D-MHD numerical simulations and synthetic observations to model magnetic fields in expanding FR II sources located at the core of a non-cool core galaxy cluster. A stratified fully ionized ICM was implemented, threaded by randomly tangled magnetic fields with a Kolmogorov power spectrum. Collimated, hypersonic and bipolar jets were injected in the centre of the computational domain. The geometry of the jets’ magnetic fields is initially random, and then shaped by the dynamics of jets. Jets form cocoons filled with light gas and magnetic fields, the structure of which is determined by both the jets’ backflow, via shear and compression, and the cocoon expansion.

We have presented five simulations exploring the parameter space given by jet-to-ambient density contrasts of $\eta = \{0.004, 0.02\}$, and jet velocities of $v_j = \{40, 80, 130\}$ Mach. We use the resulting model sources to produce synthetic synchrotron emission and linear polarisation maps at viewing angles of $\theta_v = \{30^\circ, 60^\circ, 90^\circ\}$. The simulations have taught us the following.

While we do not inject magnetic energy at the jet nozzle, the magnetic energy in jets, and their host cocoons, increases with time. The amplification is stronger for wider cocoons, which are obtained for lighter and faster jets. The main amplification mechanism is the toroidal field line stretching (Matthews & Scheuer 1990; Gaibler et al. 2009). The toroidal field is however quickly converted to poloidal field and the resulting field structure is hence a competition between MHD-turbulence and poloidal field stretching. Lighter jets are more turbulent and their magnetic field is therefore less aligned with the jet axis.

Our synthetic polarisation maps are in good agreement with radio observations (e.g. Johnson, Leahy, & Garrington 1993; Gilbert et al. 2004; Mullin et al. 2006). We generally see B-vectors that are parallel to the jet axis, tangent to the source boundaries and perpendicular to strong emission gradients. The degree of linear polarisation along both the jet axis and the source boundaries is higher than both inside and between radio lobes.

The cocoon magnetic structure shows a strong relation with $\eta$ and a rather weak relation with $v_j$. In our polarisation maps this occurs because the projected sources’ area onto the plane of the sky is proportional to the cocoons’ volume. The intrinsic polarisation angle distribution is consistently more uniform for $\eta = 0.02$ than in the lighter case. The mean polarisation angle is $\sim 10^\circ$ smaller when $\eta = 0.02$ than in the lighter case. Also, the intrinsic linear polarisation degree in the $\eta = 0.02$ case is higher than in lighter sources, i.e. when $\eta = 0.02$ we see $p$ within 46-51 per cent in the cocoons and, $\sim 63$ per cent at the sources’ edges. Conversely,
when \( \eta = 0.004 \) we see \( p \) within 25-45 per cent in the cocoons and, \( \sim 63 \) per cent at the edges. Even for our lighter cocoons, the fractional polarisation is somewhat high away from the edges and beams, which might be a resolution issue or due to the fact that our cocoons are thinner than those of most observed FR II radio sources, which is related to the jet density.

The distribution of the polarisation angle (magnetic vectors) depends on the viewing angle between jets and the line of sight, \( \theta_v \). On average we see \( \langle |\chi_B| \rangle \) decreases about 9 degrees as \( \theta_v \) goes from 30° to 60°, and about 4 degrees as \( \theta_v \) goes from 60° to 90°. In contrast, only \( p (\eta = 0.02) \) shows an increase of about 7% as \( \theta_v \) goes from 30° to 60°, and also about 3% as \( \theta_v \) goes from 60° to 90°. This is because cocoons have geometries similar to prolate spheroids, inside which the poloidal momentum flux is higher than the toroidal one. Cocoon magnetic fields are thus mainly stretched along the polar direction (the jet axis) which projection onto the line of sight is proportional to \( \cos(\theta_v) \).

We see the main features of the \( |\chi_B| \) histograms are shaped during the early expansion phase of sources, particularly for \( \theta_v \approx 60° \). In this case, magnetic fields tend to align with the jet axis as sources grow. For \( \theta_v = 30° \), on the other hand, \( \chi_b \) is distributed nearly isotropically. The fractional polarisation is broadly distributed around about 30-40 per cent, and decreases in time.

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