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Jets: an environmental impact statement

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Abstract

We review our recent work on the interaction of jets with the interstellar medium of both classical double and young radio galaxies. We propose explanations for the intriguing radio morphology of Hercules A and Pictor A in terms of the complex structure produced near the terminal shock in the jet. This also has ramifications for the interpretation of the high energy emission from Pictor A. Gigahertz Peak Spectrum (GPS) and Compact Steep Spectrum (CSS) sources are now believed to be young radio galaxies in which the jets are interacting with an inhomogeneous interstellar medium. Two dimensional slab-jet simulations of jets interacting with a clumpy interstellar medium show the way in which radiative shocks are driven into the clouds and how the jet is disrupted. There are interesting morphological comparisons between one of our simulations and the GPS source 4C31.05 and the large scale structure of M87. Another simulation with a lower filling factor, resembles the CSS quasar 3C48.

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1. Introduction

This paper represents a combination of material that was presented at two meetings: (1) The Bologna workshop, *Relativistic jets in the Chandra-XMM Era*; and (2) The Leiden meeting, *Radio Galaxies, Past, Present and Future*. In it we describe recent work in a number of areas involving interactions of radio jets and lobes with the ambient interstellar/intergalactic medium. The first two topics refer to the interactions between jets and the interstellar medium

that can lead to the formation of the unusual structures that we see in Hercules A and Pictor A. Understanding the ring-like structures in Hercules A has significant implications for how the structure of a powerful radio galaxy can be affected by its environment. Understanding the hot-spot structure of Pictor A has ramifications for the high energy emission from the hot-spot and informs us that we have to be careful in the application of simple models for inverse Compton emission. Our third topic involves the dramatically different radio structures that result when powerful jets interact with an inhomogeneous interstellar environment. This work has ramifications for young radio galaxies and for radio sources embedded in cooling flows. Viewed as a whole, these three studies provide an interesting comparison of

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the effect of a changing environment on the structure and evolution of a radio galaxy.

The numerical code that we use in this work is *ppmlr*, a modified version of the VH-1 code published by the University of Virginia (see <http://wonka.physics.ncsu.edu/pub/VH-1/>). We have enhanced this highly accurate code by the addition of thermal cooling that is important when fast shocks are driven into dense gas. We have also eliminated a classical shock instability that results in directionally split codes and which becomes much more apparent when cooling is important (Sutherland et al., 2003). We have also restructured the code for optimal execution in the Message Passing Interface (MPI) parallel environment. As a consequence it has been feasible to produce some of the simulations that are presented here in a reasonable amount of time.

2. Hercules A

It has been known for some time that the powerful radio galaxy Hercules A exhibits rather interesting structure consisting of what has been described as either rings or bubbles in the western lobe. Excellent new images of these rings are contained in the paper (Gizani et al., 2002a,b). In a recent paper (Saxton et al., 2002a), we have suggested that these rings are the result of hot-spot oscillations that become more apparent when the jet has both a low Mach number, M , and low jet to ISM density ratio, η . The conventional view of hot-spots is that they represent the emission from a reverse shock at the jet terminus.

This terminal shock is envisaged as moving slowly outwards at a speed $\sim \eta^{1/2} v_{\text{jet}}$. Variations on this theme include the Dentist-Drill Model (Scheuer, 1982) in which the hot-spot bounces from point to point within the expanding lobe. However, new axisymmetric simulations that we have conducted reveal additional effects that are particularly important when the density ratio is pushed down from the usual value $\sim 10^{-2}$ used in simulations to 10^{-3} and 10^{-4} . When this happens, the turbulence in the cocoon is capable of disrupting the jet and temporarily pinching it off. When this happens quasi-periodic surging behaviour ensues and moderately high surface brightness rings are shed by the hot-spot whose motion consists of high amplitude oscillations superimposed upon a steady outward motion.

The surface brightness snapshots in Fig. 1. show simulated surface brightness images from a Mach 5, $\eta = 10^{-4}$ viewed at an angle of 45° ¹. In all cases, ring like structure is apparent. It is also apparent that the brightest region of the source is not always at the head of the jet; for a large fraction of the time there is a recessed hot spot. These axisymmetric simula-

¹The synchrotron emissivity in this case is evaluated using the approximation that the magnetic energy density is proportional to the particle pressure, p , i.e. $B^2/8\pi \propto p$ implying that the emissivity $j_\nu \propto p^{(\alpha+3)/2}$ where α is the spectral index. At least in hot-spots, an equipartition magnetic field seems to be a good approximation in many cases, so that this approximation for the emissivity may not be too bad. In other cases such as Pictor A where the interpretation is ambiguous, an equipartition field may still be appropriate.

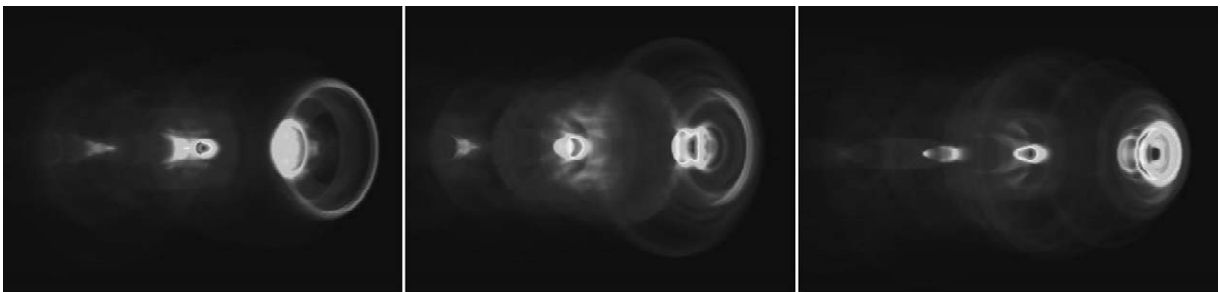


Fig. 1. Three snapshots of simulated surface brightness from a Mach 5, $\eta = 10^{-4}$ simulation of an axisymmetric jet. The simulations show rings and recessed hot-spots similar to those apparent in the radio images of Hercules A. The angle of inclination of the line of sight to the jet direction is 45° .

tions do a reasonable job of approximately reproducing the structure in Hercules A, although there it is evident that in the actual source, three dimensional effects are also important.

Why should a powerful source have a low Mach number? We have suggested that the answer may lie in the large core radius $\approx 35'' = 120$ kpc of the X-ray emission, which is much larger than the core radius ~ 1 kpc of an isolated giant elliptical. Internal to the core radius the density varies by a factor of order unity and outside it the density decreases as a power-law. An interstellar medium with this large a core is likely to decelerate the jets to the point where they become transonic, provided, of course that the jets are exposed to the interstellar medium in this region and are not protected by the cocoon. This would be the case if the cocoon does not extend all the way back to the core, or if there is substantial interstellar matter entrained in to the cocoon in this region. Another indication that the jets are transonic in the region $35''$ from the core is that the eastern jet appears to undergo a helical Kelvin–Helmholtz instability typical of a flow that is either transonic or mildly supersonic. Other features in the western jet, namely regions of rapid expansion and contraction and related knots may also be the result of re-confinement shocks induced by the declining atmospheric pressure in this region.

Why should the atmosphere of Hercules be so extended? Hercules A is in fact one galaxy in a merging pair. The gravitational field responsible for confining the gas is determined by the gravitational field of the pair of galaxies and, depending upon the distribution of dark matter in this merging system, could have a much larger core radius than that of an isolated galaxy. If this story is correct then Hercules A represents a stage in the evolution of a radio source that is intermediate between that of young GPS and CSS radio galaxies that appear to interact strongly with the interstellar medium and classical double sources in which jets are initially relatively unimpeded by either interaction with dense gas or entrainment.

One of the questions often raised in response to these ideas is whether axisymmetry is too restrictive an assumption in these models. In fact, rings in radio galaxy lobes are infrequently observed and this is consistent with the notion that in most cases, three-

dimensionality generally disrupts rings that are tending to form in the way that we have suggested.

3. Pictor A

Pictor A is another radio galaxy with unusual hot-spot morphology revealed by radio, optical and X-ray imaging. The VLT optical image (see Fig. 2) quite clearly reveals a filament of optical emission to the south-east of the hot-spot. Our view (Saxton et al., 2002b) is that this filament is the result of similar structure to that proposed for Hercules A, i.e. a ring shed by the oscillating hot-spot. In this case the ring appears to be closer to edge-on just how close depending on how much the axisymmetry of the ring is disrupted by three-dimensional effects. This also raises questions about compatibility with the one-sided X-ray jet (Wilson et al., 2001). However, the X-ray jet data are *just* compatible with an angle of about 70° to the line of sight.

Features that mimic the Pictor A observations occur less frequently in simulations of hot-spot morphology (about 1% of the time), than do the the

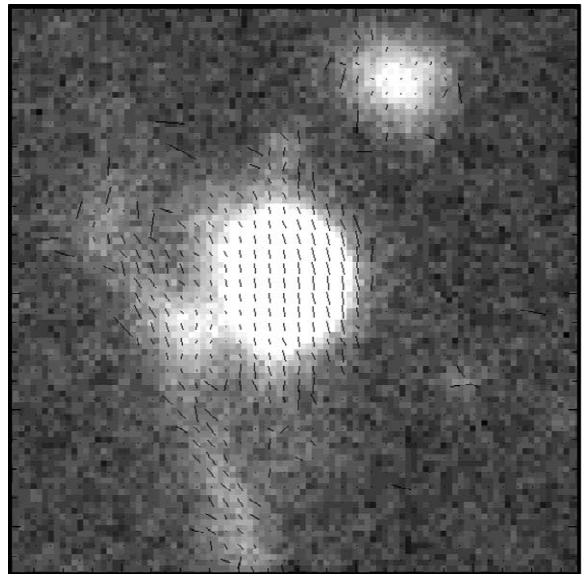


Fig. 2. The VLT optical image of the western hot-spot of Pictor A clearly showing the filament of optical emission to the south-east of the hot spot. From Saxton et al. (2002b).

ring morphologies seen in Hercules A ($\sim 50\%$ of the time). Nevertheless, snapshots from Mach 5 and Mach 10 simulations shown in Fig. 3 show features similar to those observed. Moreover, upstream of the hot-spot and filament complex, there is a fainter knot that also appears in the radio image.

Wilson et al. (2001) have also shown that the Pictor A hot-spot has a curious X-ray spectrum. In a νF_ν plot the X-ray spectrum is flat—not rising as expected from a simple inverse Compton model. Moreover, if one interprets some of the flux as arising from inverse Compton emission, the inferred magnetic field is well below equipartition. This situation may be the result of complex effects arising from both forward and reverse shocks produced by the oscillation of the hot-spot. This would result in a two

component spectrum with contributions from the cooling plasma behind each shock. There is observational support for complex structure in the optical spectral index image (Wagner et al., in preparation) that shows the steepest spectral index in the center of the hot spot—not at the northern or southern edges as might be expected from a single shock model.

4. Radiative jet–ISM interactions in Young radio sources

4.1. Physical principles

The interest in Gigahertz Peak Spectrum (GPS) and Compact Steep Spectrum (CSS) radio sources

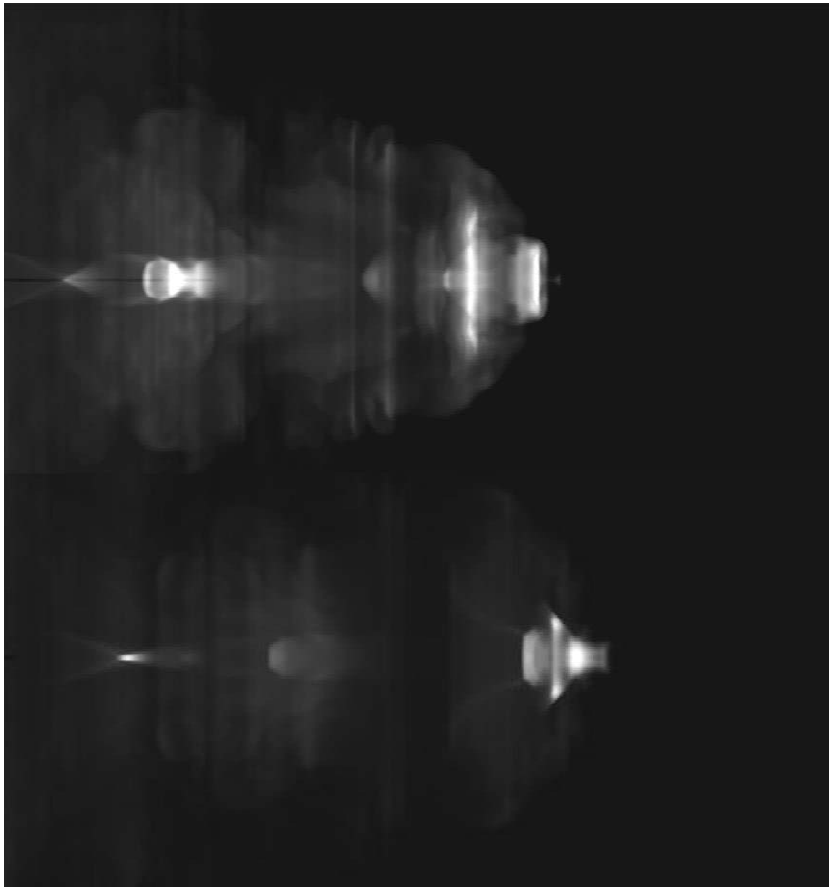


Fig. 3. Two snapshots of simulated surface brightness from a Mach 5, $\eta = 10^{-4}$ (top panel) and Mach 10, $\eta = 10^{-4}$ simulations of an axisymmetric jet. In this case the angle of inclination of the line of sight to the jet is 90° .

has steadily increased over the last decade—primarily because we are now certain that most of these sources are young rather than frustrated. They therefore represent radio galaxies in about the first 1% of their lifetime. The following brief summary encapsulates the major properties of these objects:

- The measured expansion speeds of the radio lobes are of the order of 0.1–0.4 c (Conway, 2002; Murgia et al., 1999, 2002; Murgia, 2003).
- Expansion speeds of this magnitude are consistent with the advance speed of the bowshock, v_b when its distance R from the core is calculated from the following self-similar model:

$$\frac{v_b}{c} \approx 0.14 (8 - \delta)^{-1/3} \left[\frac{F_{E,46}}{n_0 / 0.01 \text{ cm}^{-3}} \right] \left[\frac{R}{\text{kpc}} \right]^{(\delta-2)/3} \quad (1)$$

where n_0 is the total particle density in the atmosphere at a kiloparsec and δ is the index of the density variation (i.e. $n = n_0(r/\text{kpc})^{-\delta}$). The measured advance speeds therefore indicate jet powers $\sim 10^{46-47}$ ergs s^{-1} .

- The emission line gas in CS galaxies is aligned with the radio source (de Vries et al., 1997, 1999)
- The emission line gas shows systematic offsets ~ 300 – 500 km s^{-1} from the systemic velocity with full-width-half maxima ~ 500 km s^{-1} and split lines (O’Dea et al., 2002).

These emission line velocities are consistent with estimates of the velocities driven into dense clouds as a result of the pressure in the advancing radio lobe. The shock velocity is given by:

$$v_{\text{sh}} \approx 300 \left[\frac{n_{\text{cl}}/n_{\text{ism}}}{10^4} \right]^{-1/2} \left[\frac{v_b}{0.1c} \right] \text{ km s}^{-1} \quad (2)$$

Shock waves take a finite time to produce an optical display; the condition that the time for the shock to become fully radiative is less than a fraction f of the dynamical timescale is:

$$\frac{v_b}{c} < 0.06 f^{0.2} \left[\frac{n_{\text{cl}}}{100 \text{ cm}^{-3}} \right]^{0.2} \left[\frac{n_{\text{cl}}/n_{\text{ism}}}{10^4} \right]^{0.4} \left[\frac{R}{5 \text{ kpc}} \right]^{0.2} \quad (3)$$

(Bicknell et al., 2002). Given this condition it is possible that the head of the bow shock may not be completely radiative whilst the sides, with a lower shock velocity, are. This is one possible explanation for the trailing emission line morphology seen in many CSS sources (de Vries et al., 1999). Nevertheless, we are inclined to favour the idea that, in CSS sources, the radio source is breaking free of the dense cloudy region \sim a few kpc in size, near the nucleus.

Radiative shocks propagating into a dense cloud emit radiation in proportion to the pre-shock Hydrogen density, n_{H} and the shock area, with the coefficient of proportionality derived from the MAPINGSGIII code (see Dopita and Sutherland, 1995). We define a covering factor, CF, as the ratio of the area of all shocks along the line of sight and within a resolution element to the area of that element. (Hence the covering factor can be greater than unity.) Then the emission line surface brightness of [OIII] λ 5007 is given by:

$$I(\text{OIII}) = 2.3 \times 10^{-2} \times \text{CF} \times n_{\text{H}} \left[\frac{v_{\text{sh}}}{10^3 \text{ km s}^{-1}} \right] \text{ ergs cm}^{-2} \text{ s}^{-1} \quad (4)$$

This expression, combined with Eq. (2) for the shock velocity as a function of the bow shock speed can be used to estimate parameters of emission line regions when the velocity of advance is known and the shock velocities can be estimated from spectra. The calculations for two sources are shown in Table 1.

The estimated covering factors are large, especially for 3C277.1. This suggests that this model, which involves small unresolved clouds, may require some revision. This may be the initial configuration as the clouds are overrun by the source. However, as clouds are ablated, the distribution of gas may be somewhat

Table 1

Estimates of density and covering factor from [OIII] emission, shock velocities and lobe advance speed

Source	Expansion speed	n_{H} (cm^{-3})	Covering factor
3C277.1	0.04 c	6	33
3C303.1	0.07 c	14	3

different, and lower density ablated gas could be photoionized by radiation from shocks in the dense clouds. Faraday depolarization and rotation measure analysis could be useful observations in this context.

4.2. Simulations

With the above physics in mind we have been carrying out a program of simulations of powerful jets forcing their way through distributions of dense clouds. Currently, the simulations involve two dimensional slab jets. These give us an idea of the way in which the jet can be laterally deflected and also give us a good idea of what to expect in three dimensions. The initial distributions of clouds are generated using a random phase distribution in Fourier space multiplied by a powerlaw function to produce a powerlaw spectrum of fluctuations. The inverse Fourier transform produces density fluctuations representing ISM clouds. When a density threshold is applied where material with a density below the threshold being replaced by the density of a uniform hot intercloud medium, isolated clouds of dense material are formed with internal structures that reflect the powerlaw fluctuation spectrum chosen originally. By adjusting the parameters of threshold, powerlaw index and spatial scaling factor any desired cloud–intercloud density contrast and cloud filling factor may be obtained. (The filling factor in this case is the area of clouds with density above the threshold divided by the total area) Cloud sizes were limited so they contain masses consistent with galactic GMC complexes, and remain consistent with gravitational stability criteria. Regions very close to the nucleus were kept clear of clouds by applying a Roche shearing limit consistent with a 10^8 – 10^9 solar mass central black hole.

Fig. 4 shows a snapshot in $\log(\text{density})$ of a jet-ISM simulation with two dimensional parameters equivalent to a three dimensional 10^{46} ergs s^{-1} jet. This simulation has the highest filling factor that we have incorporated so far and shows intriguing structure related to the formation of different channels in the flow at different epochs. The jet power is almost completely isotropized by the interaction and the outer part of the radio structure is, in effect, an energy-driven bubble. This is confirmed by the plot shown in Fig. 5 that compares the average radius vs.

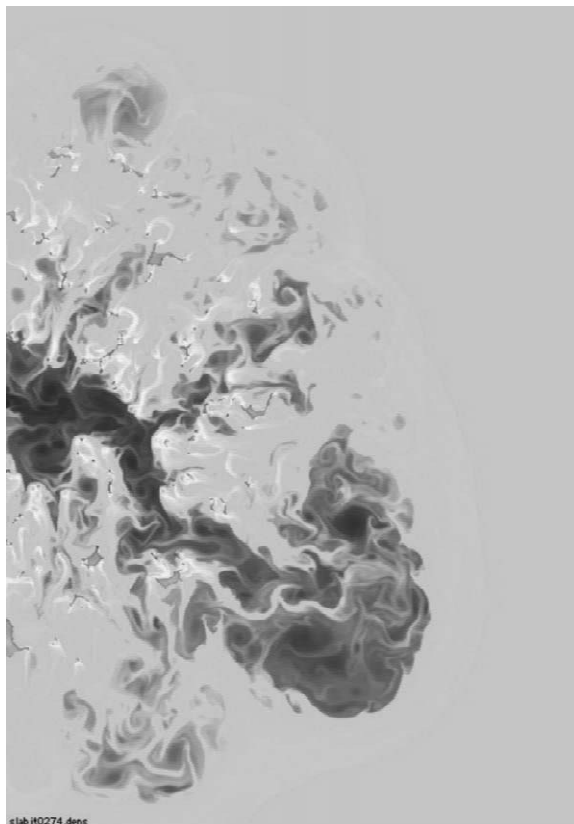


Fig. 4. Snapshot of the $\log(\text{density})$ of a slab jet interacting with a clumpy interstellar medium with a filling factor of dense clouds 2.7×10^{-3} . Note the hierarchy of structures that are formed.

time of the outermost shock in a number of different simulations compared to the prediction for a $\gamma = 5/3$ bubble:

$$R_{\text{sh}} = \frac{4}{3} \left[\frac{4A}{9\pi\rho_0} \right]^{1/4} t^{3/4} \quad (5)$$

where $A = vD \left[\frac{1}{2} \rho_{\text{jet}} v_{\text{jet}}^2 + \gamma(\gamma - 1)^{-1} p \right]$ is the power per unit length of the jet whose transverse dimension is D .

The GPS galaxy 4C31.04 (Giroletti et al., 2003) appears to show structures that are related to channeling. There is also an intriguing correspondence to M87 in that there is an hierarchy of structures ranging from inner to middle ‘lobes’ bounded by the outgoing bubble. This correspondence is appealing in that we already know that M87 exhibits emission

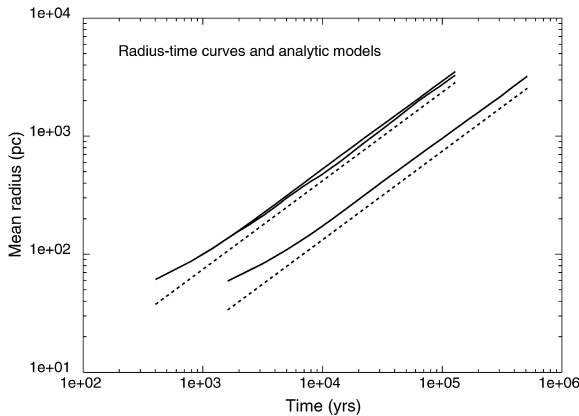


Fig. 5. Radius time curves (solid lines) for various simulations of jets interacting with clumpy media. Disruption isotropizes the jet power and a two-dimensional energy-driven bubble results. The dashed lines close to each set of solid lines represent the corresponding analytic solutions for a two-dimensional energy driven bubble.

line clouds within a couple of kpc of the nucleus (Ford and Butcher, 1979) and with which the inner lobe is clearly interacting (Bicknell and Begelman, 1996). The 75 MHz image of Owen et al. (2000) also shows filaments of radio emission that could be attributed to earlier channels of the radio-emitting plasma.

Fig. 6 shows the radio emissivity produced in a simulation with a lower filling factor (of $\approx 5.1 \times 10^{-4}$) of dense clouds. This simulation shows a striking resemblance to the inner structure of 3C48 (Wilkinson et al., 1991) and also predicts extended radio emission that is in fact observed (see the images from the 3CRR atlas maintained at Jodrell Bank: <http://www.jb.man.ac.uk/atlas/object/3C48.html>).

5. Discussion

Jets interact with the interstellar medium in complex ways. The axisymmetric jet simulations applied to Pictor A and Hercules A show that supersonic jets do not simply terminate in a shock that moves steadily outward. The terminal shock oscillates producing shocked rings and complex structure near the hot-spot. In the case of Hercules A the actual terminal shock appears to be strongly recessed.



Fig. 6. The simulated radio emissivity of a jet-ISM interaction for a 10^{46} ergs s^{-1} jet interacting with a clumpy ISM with a filling factor of dense clouds $\approx 2.7 \times 10^{-3}$. The image resembles 3C 48 both in the structure of the jet and its extended emission.

In the arena of GPS and CSS sources the influence of jets on the interstellar medium is quite dramatic. Strong emission lines are produced and the interaction renders the jets highly unstable. Indeed it was interesting to see how a small number of clouds could severely disrupt the radio source. This suggests that in classical double radio sources there is minimal jet-cloud interaction.

The simulations that we have conducted so far show promise in explaining numerous features in radio galaxies and perhaps give us new insight into the history of sources such as M87 and Centaurus A. The high filling factor simulation presented here entails a jet power about a factor of 100 too high for

M87 and the scale \sim kpc envisaged when the simulation was set up is about a factor of 10–100 too low. Nevertheless, the qualitative features of the simulation revised for these different scales should be similar. The appealing feature of the simulation presented here is that it shows a hierarchy of structures ranging from inner lobe to middle lobe encapsulated in a large bubble. We know that there are emission line clouds in the central kpc of M87 with which the radio source is interacting; possibly these are condensations from the cooling atmosphere in the central regions.

As far as 3C48 is concerned, our low filling factor simulation shows how a more or less-collimated but still disrupted outflow can be produced even with very low numbers of dense ISM in the vicinity. This sort of structure is also reminiscent of the large-scale structure of Centaurus A. In both cases there is evidence for clouds that can disrupt the jets.

We have made available on the web quicktime movies of these and numerous other simulations that we have conducted. The movies are, of course, more informative than just single snapshots. The web address is <http://macnab.anu.edu.au/radiojets/>

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