

Review: Theory and Simulations
Jet Structure, Collimation, and the role of the
Magnetic Field



Great Blue Heron, Tortuga Bay

AGN feedback by relativistic jets

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Abstract. Feedback provided by relativistic jets may be effective in shaping the galaxy luminosity function. The quenching mode (quasar mode) at redshifts ~ 2 -3 potentially disperses gas in star-forming galaxies. The maintenance mode (radio mode) heats the gas in galaxy clusters counteracting cooling flows. A number of authors have examined the effect of relativistic jets in dispersing clouds in the kpc-scale inhomogeneous interstellar medium of evolving galaxies. We have also investigated a particular case of maintenance-mode feedback in our simulation of the iconic radio galaxy / cooling flow cluster Hydra A. Modelling of the knots produced by the jets in the inner 10 kpc provides an estimate of $0.8 - 0.9 c$ for the velocities of the jets in agreement with other velocity estimates for FR1 jets. The addition of jet precession provides realistic simulations of the morphology of the Hydra A radio source and raises interesting questions as to the role of black hole and disk precession, in general, in galaxy formation.

Keywords. galaxies: active, galaxies: jets, radio continuum: galaxies

1. Introduction

To a large extent the fields of galaxy and cluster formation and large scale cosmological structure on one hand and the field of active galactic nuclei on the other, have evolved independently. This changed when the relationship between the mass of the central supermassive black hole and the mass or velocity dispersion of the bulge of the host galaxy were found to be related (Magorrian *et al.* 1998; Gebhardt *et al.* 2000; Tremaine *et al.* 2002). The initial discovery of this relation was quickly followed by an explanation in terms of feedback, in which the radiative and/or mechanical output from a black hole-fuelled quasar inhibited further galaxy formation once the black hole reached a certain size. Silk & Rees (1998) adopted energy-driven feedback in their explanation for the Magorrian relation. Fabian (1999) and King (2003, 2005) proposed feedback models in which momentum-driven feedback dominates in quasar growth (at least in the early stages). In all of these models, quasar activity drives out potential star-forming gas limiting the growth of the galactic bulge and the central black hole. This mode of feedback is now referred to as “quasar mode” or, more recently, “quenching mode”. Accordingly, all simulations of large scale structure in the expanding Universe now incorporate feedback from black holes in one form or another.

Croton *et al.* (2006b,a) introduced the concept of “radio mode” feedback in which the jet-driven lobes of radio galaxies prevent the massive inwardly directed flows that would occur in galaxy clusters as a result of X-ray cooling. Their semi-analytic models addressed another important feature of modern theories of galaxy formation – the formation of the Schechter luminosity function (Schechter 1976), which shows a marked decrease of

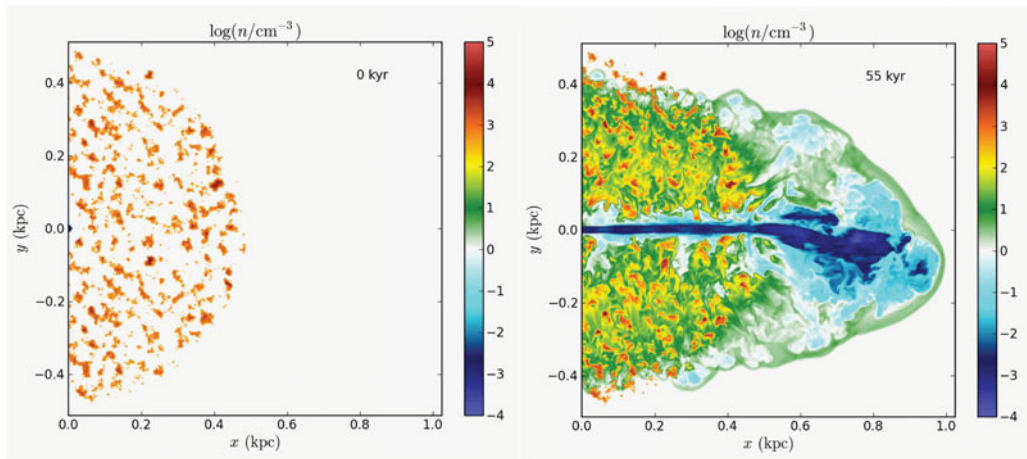


Figure 1. Interaction of a relativistic jet with the interstellar medium. Left panel: Initial spherically distributed clouds derived from log-normal, Kolmogorov distribution. Right panel: Evolution after 55 kyr. The jet power in this case is 10^{46} ergs s^{-1} , the mean warm cloud density is 300 cm^{-3} and the volume filling factor of warm clouds is 0.13.

bright galaxies compared to an hierarchical merging model. However, given that radio jets probably may also play an important role in quenching mode feedback at redshifts $\sim 2 - 3$, as first shown by Saxton *et al.* (2005) with two-dimensional simulations, a number of workers now use the term “maintenance mode” for feedback in the context of cooling flows at redshifts $\lesssim 1$.

In this review we concentrate on the role played by jets in feedback by active galactic nuclei and in particular we address the following topics: Simulations of quenching mode; the relationship to the observations of high redshift and local galaxies; the energy and momentum transfer in jet-inhomogeneous interstellar medium interactions. We then turn to a study of the radio galaxy Hydra A, which is an excellent example of the maintenance mode of jet feedback. In particular we consider the estimate of jet parameters from shock structure and the appearance of the radio galaxy as a result of jet precession.

2. Interaction of jets with inhomogeneous interstellar media

2.1. Quenching mode

When considering the role of jets in quenching mode, there is a significant departure from the above-cited early papers on AGN feedback, viz. one introduces an inhomogeneous medium, characterised by a log-normal density distribution and a Kolmogorov power spectrum in Fourier space (Sutherland & Bicknell 2007; Wagner & Bicknell 2011; Gaibler *et al.* 2012). This is more realistic than a uniform medium.

Fig. 1 shows the evolution of a 10^{46} ergs s^{-1} jet propagating into a spherical region of clouds with a mean density of 300 cm^{-3} and a volume filling factor of 0.13. The porosity of the medium arises from an imposed cutoff of 10^4 K in the temperature of the clouds, which are in pressure equilibrium with the hot interstellar medium (see Wagner & Bicknell 2011; Wagner *et al.* 2012, for details). These simulations are consistent with observations of radio galaxies in which jet-driven feedback appears to be active. The observations of MRC 0406-244, a powerful radio galaxy at a redshift of 2.42 (Nesvadba & Lehnert 2008, Fig. 9) show blue- and red-shifted gas on either side of the nucleus with

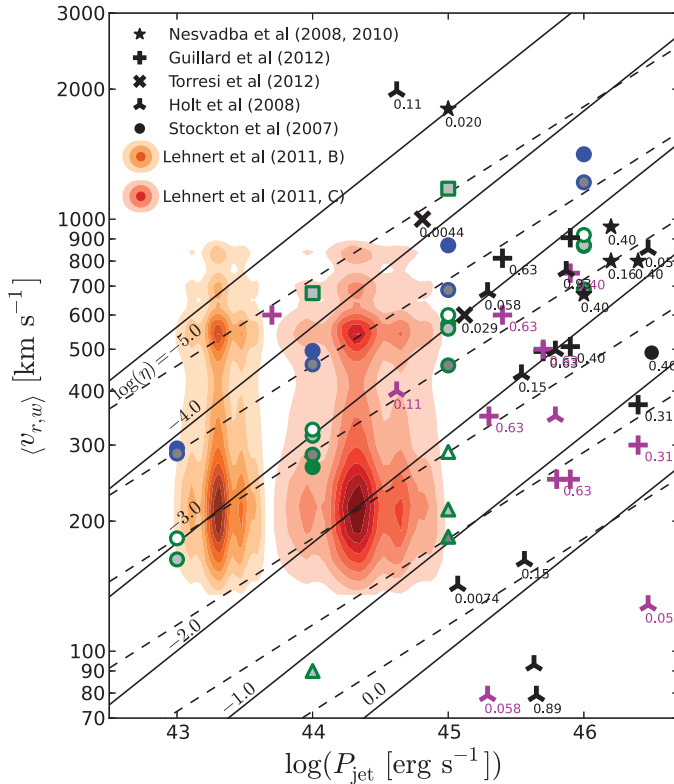


Figure 2. Simulation results and observational data in the plane defined by the outflow speed and jet power. Simulation results are shown in blue and green points corresponding to ISM hot phase densities $n_{\text{hot}} = 0.1 \text{ cm}^{-3}$ and 1.0 cm^{-3} , respectively. The samples studied by various authors are marked with different symbols and contours as shown in the legend. The black symbols mark the measured outflow speeds of ionized material, and the magenta symbols mark the measured outflow speeds of neutral material. Lines representing the locus of velocity dispersion as a function of jet power for constant values of η are superimposed. The solid and dashed lines for which the power and intercepts of the $M - \sigma$ relation $\log_{10}(M_{\text{bh}}/M_{\odot}) = B + \delta \log_{10}(\sigma/200 \text{ km s}^{-1})$ are $(\delta, B) = (4.0, 8.1)$, $(5.0, 8.1)$, respectively. Numbers attached to many of the data points denote the value of $\eta = \text{Jet power} / \text{Eddington luminosity}$. See Wagner *et al.* (2012) for details.

and the HI observations of 4C12.50, which is a young restarted radio galaxy (Morganti *et al.* 2013).

What jet powers are sufficient to drive out potential star-forming gas? Figure 2 shows the mass-weighted mean radial velocities of thermal gas in our simulations plotted against jet power. Over-plotted are a number of observational results including those from a sample of 691 radio galaxies observed by Lehnert *et al.* (2011). The lines on the diagram represent the locus of velocity dispersion as a function of jet power for jet Eddington ratios ranging from 10^{-5} to 10^0 . The location of a simulation point with respect to the Eddington ratio lines tells us for what Eddington parameters the gas velocity exceeds the galaxy velocity dispersion, which following Silk & Rees (1998), we take as the criterion for dispersal of the gas.

In addition, the high redshift radio galaxy 4C41.17, in which star formation is associated with the jet in the inner $\sim 10 \text{ kpc}$ (Bicknell *et al.* 2000), shows various extended features, for which Scharf *et al.* (2003) note “This is the highest redshift example of extended X-ray emission around a radio galaxy currently known and points toward an

extraordinary halo around such systems, where cool dust, relativistic electrons, neutral and ionized gas, and intense infrared and X-ray radiation all appear to coexist.” This points to extended interaction of the radio source with gas and dust in the Lyman- α halo associated with this galaxy. There is also a feature in the Lyman- α image on the southern side of the source, consistent with ablation of a large cloud by the expanding radio plasma.

Jets do not propagate through these clumpy media via a direct route. They are deflected by clouds and form a “flood and channel” morphology filling up a spherical region with high pressure non thermal gas. Hence radio galaxies, which we are used to considering as bipolar flows, which do not process a large fraction of the interstellar medium, in fact process a solid angle of 4π when the interstellar medium is distributed in the manner shown in Figure 1. An interesting consequence of the obstruction of the jet by randomly positioned clouds is that in a twin jet source, one jet may be more obstructed than the other, leading to an overall asymmetric morphology. This outcome was nicely simulated by Gaibler *et al.* (2011).

An interesting feature of these models is that the outflow is energy driven. The momentum of the outflow is much greater than the momentum flux in the jet integrated over time.

2.2. Jet-induced star formation

In addition to the inhibition of star formation by the processes described above, it is also necessary to consider the formation of stars induced by processes such as shock waves being driven into dense gas as a result of direct interactions between jets and clouds and indirect interactions involving the high pressured cocoon of the radio galaxy. For example, Bicknell *et al.* (2000) showed that a high rate of star formation in 4C41.17 (up to $200M_{\odot} \text{ y}^{-1}$ in one region) is associated with direct interaction between the jet and the Lyman- α halo of that galaxy. Sutherland & Bicknell (2007), in a simulation of a jet interacting with a clumpy gaseous disk, noted the radiative shocks which are driven into the disk by the high-pressured jet cocoon and which serve to keep it alight in soft X-rays. Gaibler *et al.* (2012) introduced a prescription for star formation (Rasera & Teyssier 2006) which led them to infer a ring of star formation in an initially clumpy disk (Silk 2013) has proposed that star formation, initiated by the excess pressure in a jet-inflated cocoon, would precede the quenching mode. Simulations are yet to fully address the relative importance of pressure regulated star formation and quenching in detail.

3. Maintenance mode – Hydra A

It has long been established that the feedback from jets in radio galaxies can provide enough power to counteract the cooling inferred from the X-ray emission (McNamara & Nulsen 2007), thereby preventing a “cooling flow” depositing gas, which would form stars, in the centre of the galaxy. This is an important component of the semi-analytical models for the galaxy luminosity function produced by Croton *et al.* (2006b).

Nawaz, in his Ph.D. thesis, has considered the physics of the jet interaction with a *smooth* intracluster medium through detailed models of the well known radio and X-ray cluster source Hydra A. The first step is to estimate jet parameters – in particular the jet velocity and density. Assuming that the knots in the radio jets result from reconfinement shocks as the jet comes into equilibrium with the galaxy/cluster atmosphere one can use the fact that the spacing of such knots depends on the jet Mach number. For a given jet power (in this case $10^{45} \text{ ergs s}^{-1}$ estimated from the energy budget; Wise *et al.* (2007))

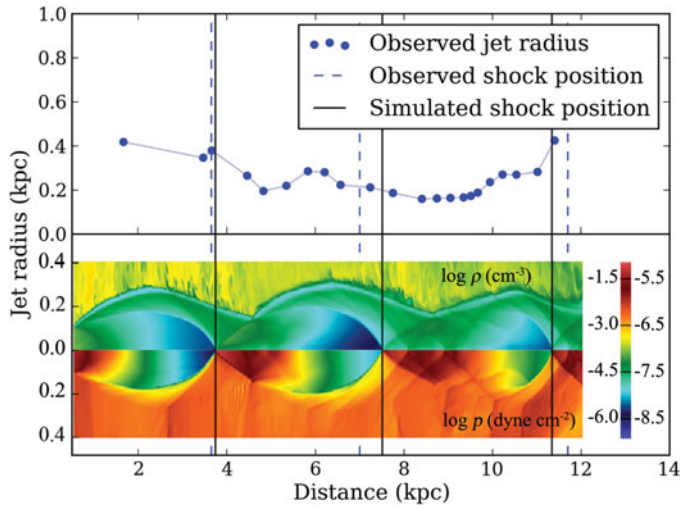


Figure 3. Comparisons of observations versus simulations in Hydra A (see text).

the spacing depends upon the velocity. An illustration of simulated reconfinement shocks and the relationship to the knot spacing is given in Fig. 3.

This reconfinement shock fitting results in the following estimates of parameters for the northern Hydra A jet at a location of 0.5 kpc from the core: Velocity $\approx 0.8c$; ratio of rest energy to enthalpy, $\chi = \rho c^2 / (\epsilon + p) \approx 13$; radius ≈ 100 pc; and ratio of jet to ISM pressures ≈ 5 .

The next step has been to take into account the curvature of the jet; this has been modelled with a precessing jet, using the parameters inferred from the straight jet model. A comparison of the resulting morphology with Hydra A is shown in Fig. 4. The optimal fit is obtained with a precession angle of 20° and a precession period of 1 My. The implications of a fairly low precession period are yet to be assessed.

One implication of precession is that the process of heating of the intracluster gas is fairly gentle. The momentum of the jet is spread over a wide area resulting in a relatively low Mach number of the bow shock of the expanding radio source. This is consistent with the conclusion by McNamara & Nulsen (2007) that the heating of clusters is gentle and spatially dispersed.

4. Concluding remarks

Four decades of research on the physics of extragalactic jets – estimates of parameters such as mass density, velocity, magnetic field, particle energy density and jet kinetic power and the relationship to the physics of black holes and accretion disks, place us in a position to apply this knowledge to another fundamental field - the physics of galaxy formation.

There are interesting problems remaining in the relation between jet physics and the formation and evolution of galaxies. As we further understand the physics of jet-driven feedback and its relationship to galaxy formation, this will feed into more realistic cosmological models and parameter free models for the galaxy luminosity function. Perhaps the most significant issue to be resolved is the balance between star formation and quenching in galaxies at redshifts of 2-3.

The involvement of precession in the physics of feedback is interesting. Potentially this has ramifications for the way the black hole is fueled and how the angular momenta of the

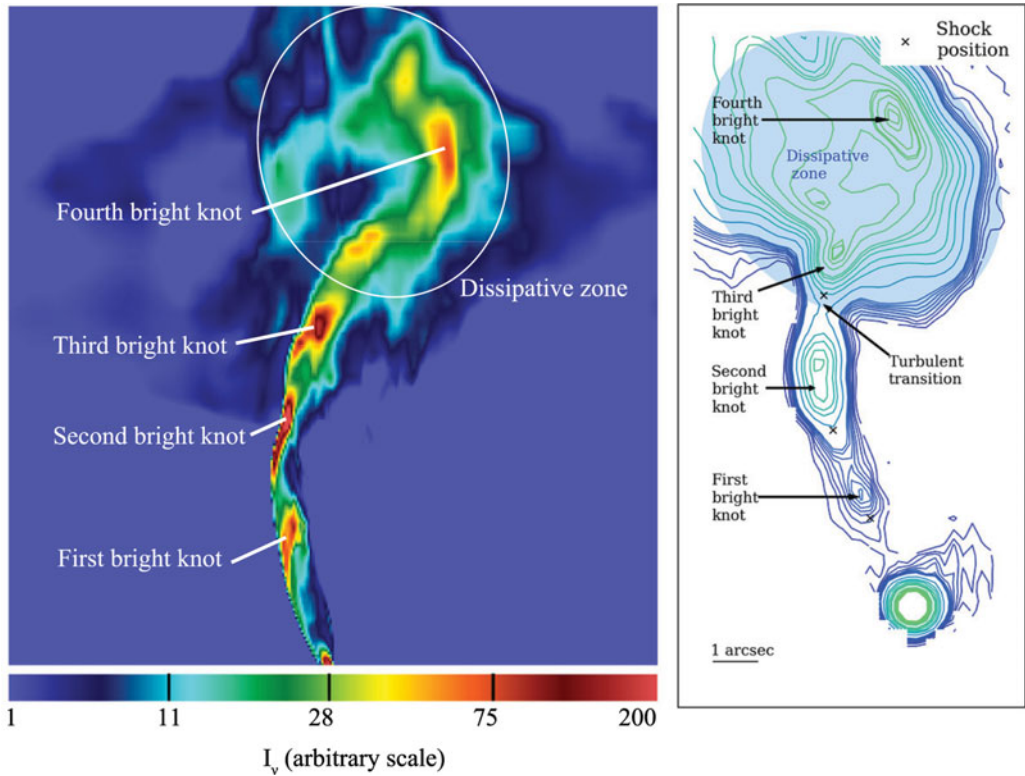


Figure 4. Model of a precessing jet with a precessional period of 1 My compared with the inner 20 kpc of the northern component of Hydra A.

black hole and the accreting matter are aligned. An interesting feature of the numerous models that came out of the parameter study of Hydra A is that a number of the other model, which did not fit the Hydra A morphology, reproduced the features of other well known radio galaxies such as Centaurus A and M 87. The timescale for alignment of the black hole and accreting angular momenta may be an important parameter in galaxy formation and feedback.

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