Periodic structure in the megaparsec-scale jet of PKS 0637–752 provides new insights into the physics of AGN jets

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Radio galaxies are a class of active galaxy. They produce highly collimated jets of relativistic plasma that emit strongly at radio wavelengths and give rise to a feedback loop between supermassive black holes and their environment known as radio-mode feedback. This feedback loop is thought to be responsible for the co-evolution of galaxies and supermassive black holes, the inhibition of cooling flows in massive clusters, and 'cosmic downsizing' — the shifting of star-formation activity from larger to smaller galaxies over cosmic time.

Despite decades of dedicated observational and theoretical study, the understanding of radio galaxies remains relatively superficial. The general paradigm, that jet production in radio galaxies is linked to accretion onto a super-massive black hole, is widely accepted, and jets are known to contain relativistic electrons that emit synchrotron radiation. However, many details more specific than these remain under debate, even fundamental issues such as: "What is the composition of radio galaxy jets?", "How exactly are the jets produced?", and "How fast are the jets on kiloparsec scales?" Radio galaxies are a fascinating phenomenon worth studying in their own right, but a detailed understanding of radio-galaxy physics is also of vital importance if we are to understand their influence on the cosmic structure we observe today.

The jets of high power radio galaxies and quasars often exhibit peaks and troughs of emission, with the peaks commonly referred to as 'knots'. In some sources, trains of bright knots with a regular or quasi-periodic pattern are observed. Understanding the physical processes that are responsible for the periodic structure seen in extragalactic jets can provide new insight into their physical conditions and dynamics.

As part of a campaign to study kiloparsec-scale quasar jets with strong X-ray emission, we observed a sample of 14 flat-spectrum radio quasars at 20 GHz with the Compact Array in the 6-km configuration, which provided 0.5-arcsecond angular resolution. These observations enabled detailed mapping of the jet structure, and in one of our targets, PKS 0637-752, they revealed a spectacular train of quasi-periodic knots extending 11 arcseconds along the jet (see Figure 1). The periodic nature of the knots in PKS 0637–752 is striking, and in a recent article based on the 20-GHz Compact Array image (Godfrey *et al.* 2012) we pose the question: what physical process is responsible for the periodic knot structure? Are the knots a static pattern through which the flow travels or a real variation within the flow, caused by a variable jet engine?

If the knots are a static pattern, the most obvious possibility is that they are due to re-confinement or 'pinching' shocks, produced as the jet expands and contracts periodically along its length in an attempt to match the pressure of the surrounding material, and repeatedly overshooting the equilibrium position. Because the jet is supersonic, this expansion and contraction of the jet boundaries would result in a network of criss-crossed shock waves, or 'shock diamonds', which would cause a brightening of the jet emission (the knots). Re-confinement shocks are commonly observed in laboratory jets, as well as in supersonic outflows on Earth such as the afterburner exhaust of reconnaissance

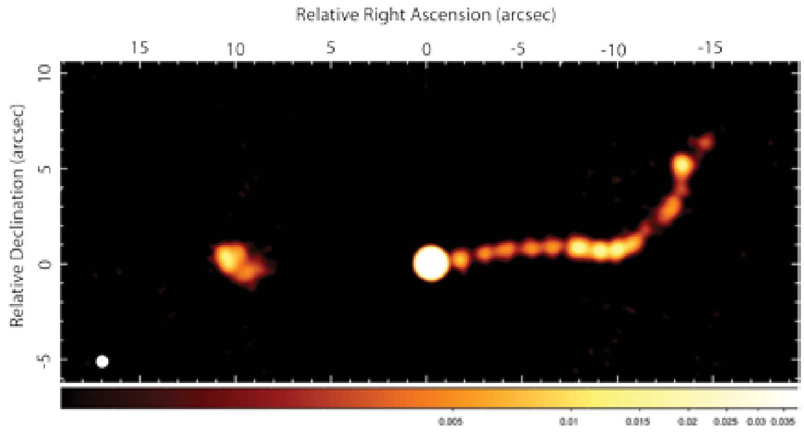

FIGURE 1:
An 18-GHz image of the large-scale jet of PKS 0637-752, made with the Compact Array. Note the regularly spaced peaks of emission that occur along the jet.

FIGURE 2:
A Blackbird reconnaissance aircraft, with afterburners on. Note the regularly spaced peaks of emission in the outflow from the afterburners. These peaks of emission correspond to 'diamond shocks' in the supersonic outflow, and bear a striking resemblance to the regularly spaced peaks of emission in the extragalactic jet of PKS 0637-752.

jets (see Figure 2), and in hydrodynamic simulations of AGN jets. Interpreting the knots in PKS 0637-752 as re-confinement shocks provides an estimate of the jet kinetic power $Q_{jet} \sim 10^{46}$ ergs per second. However, if the knots are indeed due to re-confinement shocks, and the jet is expanding into a realistic external medium with radially decreasing density profile, we would not expect the knot spacing to remain constant all along the jet (Saxton *et al.* 2010).

How might the knots be produced by modulation of the jet engine? In this class of model, the knots are associated with periods of heightened output from the central engine. We find that the modulation period implied by the observed periodic structure is 2,000 yr < T < 300,000 yr, with the lower end of this range applicable if the jet remains highly relativistic on kiloparsec scales, as implied by models of the jet's X-ray emission. We suggest that the periodic structure in PKS 0637–752 may be analogous to the quasi-periodic modulation seen in the jet of the microquasar GRS 1915+105 on a timescale of 30 minutes, which is believed to result from limit-cycle behaviour in an unstable accretion disk (see, for example, Fender & Belloni, 2004). Accretion disk instabilities are expected to produce quasi-periodic modulation of the jet output due to modulation of the accretion rate. The physical timescales are expected to scale linearly with the mass of the black hole, and therefore, the T ~ 30 minute oscillations in the jet of GRS 1915+105 (MBH ~ 14 $M_{\odot}$) extrapolate to T ~ 2,000 yr for PKS 0637–752 (MBH ~ 5×10^8 $M_{\odot}$), consistent with the modulation timescale inferred from the periodic jet structure.

Finally, the variations in the accretion rate might be driven by a binary black hole. In this case, the predicted orbital radius is 0.7 pc < a < 30 pc, which corresponds to a maximum angular separation of 0.1–5 milli-arcseconds.

Other mechanisms, such as Kelvin-Helmholtz instabilities, may be possible. Follow-up observations of this object at higher angular resolution with the Compact Array, and observations of other objects showing quasi-periodic jet structure (such as those in Figure 3), will enable us to discriminate better between the various models of periodic knot production, providing an additional clue to the nature of radio galaxies — the powerful instruments of radio-mode feedback.

References

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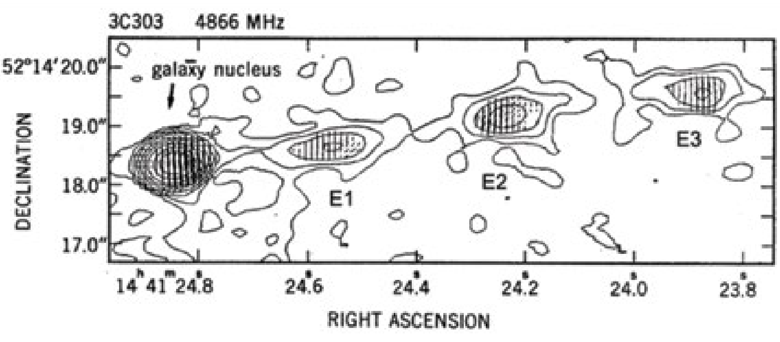

FIGURE 3:
Two more examples of radio galaxy jets showing periodic structure on kiloparsec scales. Top: VLA image of 1919+479 at 6 cm from Burns et al. (1986). Bottom: VLA image of 3C 303 at 4.9 GHz from Kronberg (1986).