ORIENTATION EFFECTS ON BENT EXTRAGALACTIC JETS

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Abstract. We have investigated how varying several parameters affects the results of a collision between an extragalactic jet and a dense, intergalactic cloud, through a series of hydrodynamic simulations. We have produced synthetic radio images for comparison with observations. These show that a variety of structures may be produced from simple jet-cloud collisions. Moderate Mach numbers and density contrasts are needed to produce observable bends. We investigate the effect of viewing from various angles on the appearance of such sources.

1. Observations of distorted jets

The jets and hotspots of radio galaxies and quasars often show complex structure. Jets can bend by over 90° and remain collimated for several jet radii (Bridle and Perley, 1984), despite the expectation that the oblique shock causing the bend should decelerate the jet (Icke, 1991). Barthel et al. (Barthel et al., 1988) present a large sample of quasars in which 25% showed bending greater than 20°. Explanations for these complex structures
include collision with dense clouds in the ambient medium (Stocke, Burns and Christiansen, 1985; Lonsdale and Barthel, 1998).

In studies of astrophysical fluid dynamics we can only measure the emission properties of sources as projected onto the sky. We must infer flow properties from such observations. In numerical simulations we must attempt to invert this by estimating the emission properties of our solutions and considering the effect of the projection of three-dimensional solutions onto two-dimensional observations. We present the results of such studies, along with some tentative conclusions, in section 4.

2. Jets and their interaction with environment

Much of the understanding of the fluid dynamics of extragalactic jets, and of the shape and structures found in observations, has come from numerical simulations (Williams, 1991). Fully three-dimensional simulations have only become possible fairly recently (Norman, 1993), but many important results have been obtained from axisymmetric calculations. Several models for the production of complex and distorted structures in radio jets and lobes have been explored through numerical simulations including: variations in the direction of the jet at its source (Williams and Gull, 1985; Scheuer, 1982); cross-winds (Leahy, 1984); the source axis is not parallel to the axis of a spheroidal gas distribution, or the source galaxy moves through the cluster medium (Leahy and Williams, 1984); helical instabilities (Steffen et al., 1997); oblique magnetic fields in the intra-cluster medium (Koide et al., 1996). Cloud collisions are particularly applicable in cases where these bends are very sharp. Loken et al. (Loken et al., 1995) show that the necessary gas velocities can arise in cluster mergers, as can shocks that will bend the jet. These simulations still do not explain the sharpness of the bend.

The first investigation of the effect of off-axis jet-cloud collisions was by De Young (De Young, 1991) using the ‘beam scheme’ (Sanders and Prendergast, 1974). De Young observed that the jet was decelerated by the cloud. A similar interaction was investigated at higher resolution by Balsara and Norman using their RIEMANN code (Norman, 1993). They argued that a De Laval nozzle was formed which re-accelerated the jet in a
new direction after impact. They did not present any results at later time to show the formation of a deflected flow pattern.

More recently Raga and Canto (Raga and Canto, 1996) have published analytical calculations and two-dimensional simulations showing bending by clouds. They conclude that slower jets will be bent more, and clouds will be eroded as jets bore through them.

3. Numerical methods

We have extended this work through a series of simulations using various sets of parameters (Higgins, 1998; Higgins, O’Brien and Dunlop, 1999). The parameters are: Mach number, and the density contrasts between of the jet and the cloud with the ambient medium. Details of the simulations are given in table 1. We have assumed conditions in the ambient medium consistent with observations: a temperature of $5 \times 10^7 \text{K}$ and a particle number density of $0.01 \text{ cm}^{-3}$. These values are used to form dimensionless units in the computation so that model values for the ambient density and pressure in the code are set to 1.0. The jet and cloud are both taken to be in pressure balance with the ambient medium.

To calculate the synchrotron emission we need to express the magnetic field and the energy distribution in terms of the results of our hydrodynamic simulations. We can then produce synthetic radio maps by integrating this through the grid. We used the data visualization package PV-Wave to examine the simulations. This has the facility to rotate three-dimensional data sets, and hence integrate along any chosen line of sight.

| Simulation number | Jet density contrast | Cloud density contrast | Jet mach number | Jet speed |
|-------------------|---------------------|-----------------------|-----------------|----------|
| 1, 2, 9           | 0.01                | 50, 200, –            | 2               | 0.07c    |
| 3, 4, 10          | 0.01                | 50, 200, –            | 10              | 0.36c    |
| 5, 6, 11          | 0.2                 | 50, 200, –            | 2               | 0.02c    |
| 7, 8, 12          | 0.2                 | 50, 200, –            | 10              | 0.08c    |
4. Results

The interactions produce a variety of structures depending on the values of these parameters, so this model can be applied to many radio structures. Different structures can also be produced by a single set of parameters as the interaction progresses. Strong deflections ($\sim 90^\circ$) are difficult to sustain, producing transient structures with complex features such as double hotspots. Deflection may be easier to produce or detect in lower power jets close to the plane of the sky. This is the case for simulations 3 and 4. As the jet breaks through the cloud there are two hotspots within a boot-shaped lobe. This is a similar radio structure to 4C 29.50 (Lonsdale and Barthel, 1986), with the close double hotspot. Although the cloud impact is the cause of the bending, the deflection and secondary hotspot is actually produced as the jet bends inside the distorted cocoon that has been formed during the interaction.

It is difficult to reach firm conclusions on the basis of these simulations of the kind of sources, and how many of any kind, we would expect to observe. We need to know how sources are distributed over the ranges of parameters, how the environments vary in clumpiness and density and hence what the probability of colliding with a density enhancement is. However we can make crude estimates of the likely distribution of sources by assuming fairly uniform distribution of the parameters characterising the jets and their environments. Figure 1 shows contour plots of the radio intensity of simulation 4 at two epochs (at $t = 4$ and 8). These show that the secondary hotspot that forms after impact is about one order of magnitude fainter than the primary hotspot at the impact. The line connecting the two hotspots is about $90^\circ$ to the axis of the initial jet direction, which would be interpreted in observations as a $90^\circ$ bend. It is about one jet radius long, but the observed width of the jet is smaller than the real width, due to limb darkening, so in observations this might be interpreted as a few jet radii. By the next epoch the secondary hotspot has faded by an order of magnitude or so, while the angle has increased to $120^\circ$.

Clearly this would be difficult to detect without huge dynamic range (signal to noise), and the $90^\circ$ structure only lasts for at most a single
epoch of the interaction. This is no more than 15% of the lifetime of the interaction. This interaction is itself short lived, perhaps 10% of the typical lifetime of a radio source ($10^8$ years), so we would expect only 1–2% of sources with these parameters, viewed in the plane of the sky, to show 90° bends.

Figure 2 shows the radio emission from simulation 4 at $t = 4$ at several orientations. Each column shows the source rotated by 30° intervals, and each row is tilted 30° toward the line of sight. The 90° bend is only visible for a few orientations. Assuming such sources are distributed isotropically with viewing angle, we would only expect to detect about 20%. Thus we would only expect to see between a third and a half a percent of sources with these parameters.

These simulations are the only one of the four sets of jet parameters that show a 90° deflection with a secondary hotspot. If this is a representative sampling of jet parameters then we would expect at most a quarter of all sources to fall into this region. Thus we expect a total of one-tenth of a percent of all radio sources to show this sort of extreme bend.

Bent jets seem to be more common than this. It would appear that the conditions to produce bends are more common than we have assumed. The jet may interact with more than one cloud, extending the lifetime
and the likelihood of observation. More detailed simulations and better statistics of such bends may allow us to estimate the number of sources with a sufficiently clumpy medium to make collisions likely. An observational study of the true statistics of bent jets may allow us to predict the number of sources with a sufficiently clumpy medium to make collisions likely.

We have simulated the passage of a jet through a medium containing an ensemble of clouds in (Higgins, O’Brien and Dunlop, 1999; Higgins, 1998). As the jet progresses through the grid it is deflected several times where it has encountered clouds, but can clearly be defined through the chain of knots, whose total lifetime is much longer.

Figure 2. Integrated radio emission from simulation 4 ($M = 2, \eta_j = 0.01, \eta_c = 200.0$) at various angles.
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