

# **Part 4. Recycling**

## **Intergalactic Star Formation**

## Jet–Induced Star Formation

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**Abstract.** Jets from radio galaxies can have dramatic effects on the medium through which they propagate. We review observational evidence for jet-induced star formation in low (‘FR-I’) and high (‘FR-II’) luminosity radio galaxies, at low and high redshifts respectively. We then discuss numerical simulations which are aimed to explain a jet-induced starburst (‘Minkowski’s Object’) in the nearby FR-I type radio galaxy NGC 541. We conclude that jets can induce star formation in moderately dense ( $10\text{ cm}^{-3}$ ), warm ( $10^4\text{ K}$ ) gas; that this may be more common in the dense environments of forming, active galaxies; and that this may provide a mechanism for ‘positive’ feedback from AGN in the galaxy formation process.

### 1. Introduction

Observations suggest that large scale, shock-induced star formation is an integral part of the galaxy evolution process. It is important in colliding and merging galaxies such as the Ultra-Luminous Infrared Galaxies (ULIRGs) and in forming galaxies. It may also occur to a lesser extent near the central dominant galaxies in cooling flow clusters and in galaxies moving through dense cluster atmospheres. Perhaps the most spectacular shock-induced star formation occurs as the result of the collision of extragalactic radio jets with over-dense ambient material. Here we review existing observational evidence in support of jet-induced star formation in both nearby and distant radio galaxies. We will then discuss numerical simulations performed at the University of California Lawrence Livermore National Laboratory which are aimed to explore the conditions under which such star formation may occur, and apply this to the nearby ‘Minkowski’s Object’ (M.O.).

### 2. Environments of radio galaxies

Radio galaxies do not live in a ‘vacuum’ but are surrounded by gaseous halos and/or debris from recent merger events which may have triggered the radio galaxy activity in the first place. Broadly speaking one can discriminate between the low-luminosity Fanaroff and Riley FR-I types (such as 3C 31), which have expanding, turbulent jets without terminal shocks or hotspots, and the high luminosity FR-II types (such as Cygnus A) which have very well collimated jets ending at high surface brightness hotspots and large diffuse lobes (Fanaroff and

Riley 1974). FR-I's may be found in clusters of galaxies where they can interact with cooling clouds in the Inter Galactic Medium (Ferland et al. 2002). At high redshift ( $z > 2$ ), because of sensitivity limits, only the FR-II types are easy to detect. Since they inhabit young, forming galaxies their jets propagate through relatively dense and clumpy media. Observational evidence for this dense and cool gas in high redshift radio galaxies has been plentiful and includes the detection of dust, HI, extended line emission, associated absorption line systems and molecular gas (e.g. De Breuck et al. 2003).

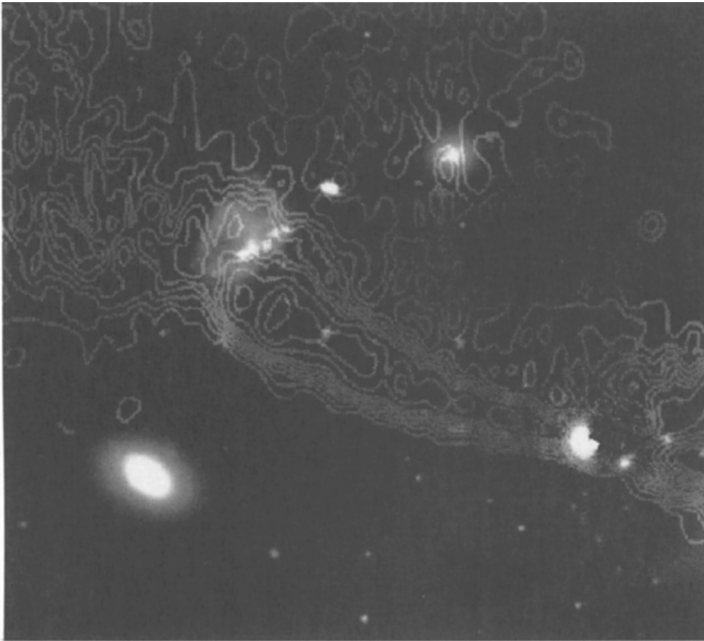


Figure 1. Jet-induced starburst in Minkowski's Object, the peculiar object at the end of the radio jet from NGC 541 (contours, galaxy subtracted; van Breugel et al. 1985)

### 2.1. Jet-induced star formation in nearby FR-I type radio galaxies

One of the first radio galaxies where evidence was found for jet-induced star formation was the nearest radio galaxy, Centaurus A (Blanco et al 1975). Further examples have been found as the sensitivity and spatial resolution of radio and optical telescopes has improved. In the case of Centaurus A, recent observations with the Hubble Space Telescope, when compared to radio images obtained with the Very Large Array, have confirmed that there are about half a dozen young ( $< 15$  Myr) OB associations near filaments of ionized gas located between the radio jet and a large HI cloud (Mould et al. 2000). Another nearby example is 'Minkowski's Object', a peculiar small starburst system at the end of a radio jet emanating from the elliptical galaxy NGC 541, located near the center of the cluster of galaxies Abell 194 (van Breugel et al. 1985). Star forming regions

associated with radio sources have also been found in cooling flow clusters, with the best example being in Abell 1795 (McNamara 2002).

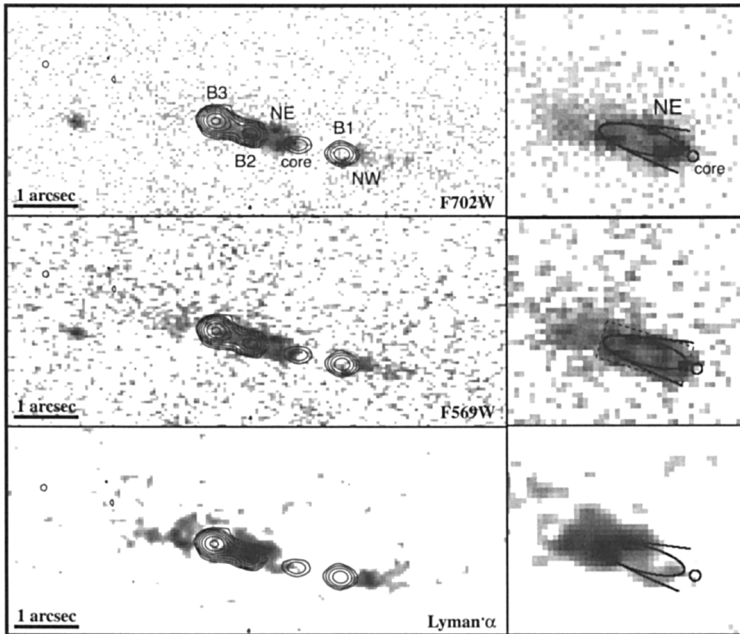


Figure 2. Jet-induced star formation in the  $z = 3.8$  FR-II radio galaxy 4C41.17 (Bicknell et al. 2000)

## 2.2. Jet-induced star formation in distant FR-II type radio galaxies

Radio galaxies have now been identified up to  $z \sim 5.2$ . They are the most massive galaxies at any redshift and, at high redshift, are usually associated with extended, clumpy systems. Many have giant Ly- $\alpha$  halos, dust and CO molecular gas. One of the most striking correlations in  $z > 0.6$  radio galaxies is that their optical line and continuum emission is aligned with the radio sources (McCarthy et al. 1987; Chambers et al. 1987). The best studied example here is 4C41.17 at  $z = 3.8$ , where deep spectroscopic observations have shown that the bright, spatially extended, rest-frame UV continuum emission aligned with the radio axis of this galaxy is unpolarized and shows P Cygni-like features similar to those seen in star-forming galaxies (Dey et al. 1977).

Collectively, these observations are best explained by models in which shocks generated by the radio jet propagate through an inhomogeneous medium and trigger gravitational collapse in relatively overdense regions (Begelman et al. 1989; De Young 1989; Rees 1989). A detailed analysis of the jet-induced star formation in 4C41.17 has been presented by Bicknell et al. (2000). In that object, Hubble Space Telescope images showed a bimodal optical continuum structure parallel to the radio jet, strongly supporting the idea that the star formation was triggered by sideways shocks.

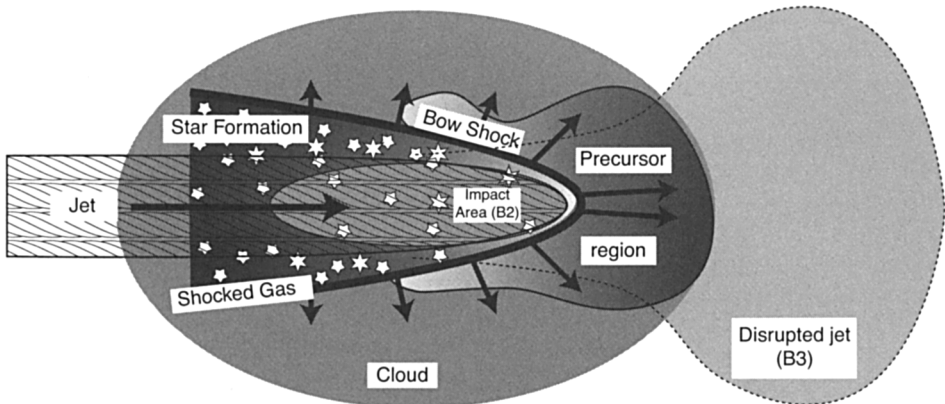


Figure 3. Model showing how sideways shocks by expanding radio lobes in an FR-II type radio source may induce star formation in the dense ambient medium of a forming galaxy (Bicknell et al. 2000)

### 3. Minkowski's Object

One of the most spectacular observed jet-induced starbursts is 'Minkowski's Object' associated with the elliptical galaxy NGC 541 in the cluster of galaxies Abell 194 (van Breugel et al. 1985). Its morphology is strongly suggestive of a collision between the FR-I type jet from NGC 541 and a dense cloud: M.O. has the same overall diameter as the jet, appears wrapped around the end of the jet, has bright emission in the upstream direction and filamentary structure down-stream where the jet appears disrupted. Spectroscopically M.O. looks like an HII region, resembling starburst galaxies. The  $H\alpha$  luminosity suggests a modest star formation rate of  $0.3 M_{\odot} \text{ yr}^{-1}$ . VLA observations (van Breugel and van Gorkom, unpublished) show two detections down-stream from the jet-cloud collision site, indicating a total HI mass of  $\sim 3 \times 10^8 M_{\odot}$ .

### 4. Numerical simulations

The basic idea of shock-induced star-formation is that when a strong shock passes through a clumpy medium it may trigger many smaller-scale compressive shocks in overdense clumps. These shocks increase the density inside the clumps and make it possible for them to radiate more efficiently. If the radiative efficiency of the gas has a sufficiently shallow dependence upon the temperature, then radiative emissions are able to cool the gas rapidly, in a runaway process, producing even higher densities as the cooling gas attempts to re-attain pressure balance with the surrounding medium. Both the reduction in temperature and the increase in density act to reduce the Jeans mass, above which gravitational forces become important. Any clump that was initially close to this instability limit will be pushed over the edge and forced into gravitational collapse. Thus, the passing of a shock through a clumpy medium may trigger a burst of star

formation. Several processes, acting on different timescales, govern whether or not cooling and star formation are able to proceed.

To investigate under which conditions shock-induced star formation can occur requires numerical simulations. This also provides information about environments that may be observationally out of reach, such as in forming galaxies at high redshift, and which could be important for understanding the role of jets in the feedback of active galactic nuclei (AGN) on their environment. Numerical simulations can also give us insight into the role of shock-induced star formation in other environments such as supernova shocks and cloud-cloud collisions.

The interaction of a strong shock with non-radiative clouds has been the subject of many numerical studies (e.g. Klein et al 1994; Poludnenko et al 2002). For a non-radiative cloud the passing shock ultimately destroys the clouds within a few dynamical timescales. Destruction results primarily from hydrodynamic instabilities at the interface between the cloud and the post-shock background gas.

The effects of strong shocks interacting with radiative clouds are very different and studies of this have only recently begun (Mellema et al. 2002; Fragile et al. 2003). Instead of re-expanding and quickly diffusing into the background gas, the compressed cloud instead breaks up into numerous dense, cold fragments. These fragments survive for many dynamical timescales and are presumably the precursors to star formation. Previous work has focused primarily on FR-II type radio galaxies even though, because of their proximity, much better observational data can be obtained for FR-I type jet-induced starbursts such as M.O. Fragile et al (2003) used the LLNL developed, multi-dimensional, multi-physics, massively parallel ‘COSMOS’ numerical simulations package (Anninos et al. 2003; Anninos and Fragile 2003) to investigate both FR-I and FR-II type jet-induced star formation systems.

#### 4.1. Application to Minkowski’s Object

To simulate the jet induced star formation in M.O. Fragile et al (2003) assumed that NGC 541 is surrounded by a multi-phase medium resembling cluster atmospheres (e.g. Ferland et al. 2002). Specifically, it was assumed that the FR-I jet interacts with a moderate density, hot ‘mother’-cloud with a semimajor axis of 10 kpc, a semiminor axis of 5 kpc, a density  $n_{mcl} = 0.1 \text{ cm}^{-3}$ , and temperature  $T = 10^6 \text{ K}$ . This corresponds to an initial total cloud mass of  $\approx 10^9 M_{\odot}$ . Within this mother-cloud denser, warm clouds were assumed to be embedded with typical sizes of 100 pc,  $n_{cl} = 10 \text{ cm}^{-3}$ , and temperature  $T = 10^4 \text{ K}$ .

The detailed radio and X-ray study of the proto-typical FRI-type radio galaxy 3C31 by Laing and Bridle (2002) was used to estimate plausible jet parameters near M.O., at  $\sim 15 \text{ kpc}$  from the NGC 541 AGN. We assumed that the long axis of the mother-cloud is aligned with a jet of high velocity ( $0.3c$ ), low density ( $10^{-4} \text{ cm}^{-3}$ ) gas flowing onto the grid. The diameter of the jet nozzle is equal to half the diameter of the cloud along the semiminor axis.

Our numerical simulations consisted of two parts. To investigate the overall structure of M.O. we followed the evolution of the collision of the jet with the low density mother-cloud. To determine whether star formation can be triggered we followed the evolution of shocks interacting with one or more of the dense, warm clouds embedded in the mother-cloud.

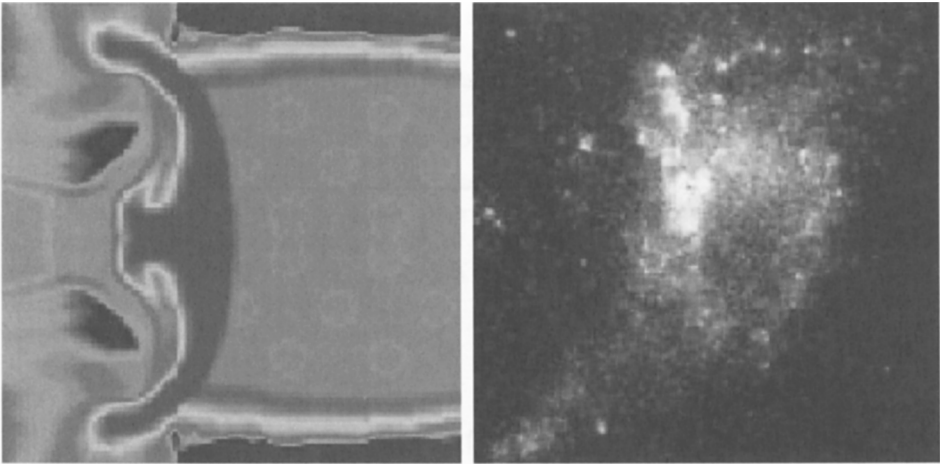


Figure 4. Comparison of an intermediate density distribution plot from the numerical simulation with a similarly scaled observation of Minkowski's Object (rotated for easy comparison). There are clear similarities between the distribution of the post-shock gas within the simulated cloud and the regions of active star formation within Minkowski's Object.

The collision with the mother-cloud triggers a nearly planar shock down the long axis of the cloud. As the bow shock from the jet wraps around, it also triggers shocks along the sides of the cloud. A similar shock structure may explain the filamentary nature of the star-forming region in M.O. (Fig. 4). To determine whether the clouds embedded within the mother-cloud would indeed collapse and form stars we ran a number of simulations to explore the density-velocity parameter space. These results are summarized in Figure 5.

## 5. Conclusions

From our numerical simulations, when applied to M.O., a number of important conclusions can be drawn. First, its peculiar morphology - bright star forming region orthogonal to the jet, and fainter filamentary features downstream from there - can be easily reproduced by our simulations. Second, the modest amount star formation required -  $0.3M_{\odot} \text{ yr}^{-1}$  for the entire object, is also easily achieved for the plausible parameter space explored by our simulations. Third, and most interestingly, we conclude that the star formation in M.O. could be induced by a moderate velocity jet ( $9 \times 10^4 \text{ km s}^{-1}$ ) interacting with a collection of slightly overdense ( $\sim 10 \text{ cm}^{-3}$ ), warm ( $10^4 \text{ K}$ ) clouds, i.e. it is NOT necessary to assume that this was an accidental collision between a jet and a preexisting gas-rich galaxy. This also suggests that the neutral hydrogen associated with M.O. ( $3 \times 10^8 M_{\odot}$ ; van Breugel & van Gorkom, unpublished) may have cooled from the warm gas phase as a result of the radiative cooling triggered by the radio

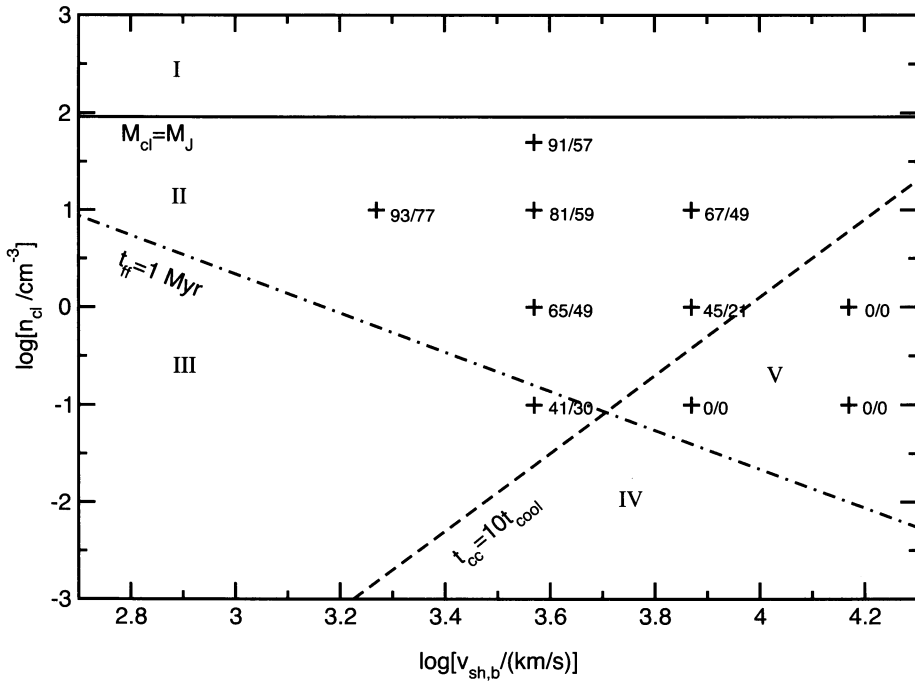


Figure 5. General cloud number density ( $n_{cl}$ )-shock velocity ( $v_{sh,b}$ ) parameter space considered. The solid line demarks the density above which the cloud is initially gravitationally unstable (region I). The dashed line divides the cooling dominated regions (II & III) on the left from the non-cooling regions (IV & V) on the right. The dot-dashed line is an estimate of the star-formation cut-off. The parameter pairs explored with the equilibrium cooling curve model are indicated with crosses. The numbers give the percent of the initial cloud mass that ends up below  $T = 1000$  and  $100$  K, respectively.

jet. An update on the observations of M.O. will be presented in a forthcoming paper (S. D. Croft et al., in preparation).

Our models can be used to infer the importance of shock-induced star formation in other regimes by simply adjusting the criteria used to develop Figure 5. They have confirmed the reality of the division between regions II and V (cooling and non-cooling) derived using approximate analytical methods, while the other region boundaries are set by physical limits for the clouds. Our key conclusion is that shocks associated with jets may indeed trigger the collapse of clouds to form stars. Whether this occurs at the impact area, or along the sides of expanding lobes depends on jet power and the ambient gas density distribution. In forming galaxies, where both dense gas and AGN activity are likely,



jet-induced star formation might help trigger even more star formation, at an earlier stage, then otherwise might have occurred.

In future work, we shall expand our numerical simulations package to include Adaptive Mesh Refinement and magnetic fields and will investigate regimes appropriate for other possible shock-cloud interaction scenarios.

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