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The radio/optical alignment of high-z radio galaxies: triggering of star formation in radio lobes

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Summary. A young galaxy would contain clouds or filaments with $T \lesssim 10^4$ K in pressure balance with a medium at $T \gtrsim 10^6$ K. When activity in its nucleus turns such a galaxy into a strong radio source, shocks propagate through this two-phase gas, inflating radio lobes filled with relativistic plasma. The shocks expel the hot-phase gas, but leave the clouds within the lobes, where they are squeezed by the higher pressure. This compression pushes many clouds over the threshold for gravitational instability, thereby triggering a burst of star formation. This process may account for the recently discovered alignment of optical and radio structure in high-z radio galaxies.

1 Introduction

The optical detection of many high-z radio galaxies has led to the important discovery that these are distinctively different from their counterparts at lower redshifts. For a sample with $z > 0.6$, the visible light – emission lines and an underlying continuum component – is preferentially aligned with the radio axis (McCarthy *et al.* 1987b; Djorgovski *et al.* 1987; Chambers, Miley & van Breugel 1987, 1988b; Chambers, Miley & Joyce 1988a; Lilly 1988). The obvious interpretation is that the radio outburst triggers a burst of star formation; other options cannot yet be excluded, and the existing data on high-z radio galaxies may embrace more than one phenomenon (e.g. Chambers *et al.* 1988a; Fabian 1989). In this paper, I consider how enhanced star formation might indeed be triggered in a radio galaxy, and why the effect should be more conspicuous in sources at high redshifts.

2 The state of the gas in a galaxy at $z \gtrsim 2$

At $z = 2$, galaxies would still be in the process of forming. Quite general considerations (see, e.g., Rees 1988) suggest that infall of gas from radii up to 100 kpc would continue for $\gtrsim 10^9$ yr. This infalling material could be heated to the virial temperature (10^6–10^7 K) by shocks and adiabatic compression. Gas with $T = T_{\rm virial}$ would occupy most of the volume; embedded in it, however, would be clouds or filaments at $\lesssim 10^4$ K. Some kind of two-phase structure is almost inevitable, because $\mathscr{R} = t_{\rm cool}/t_{\rm free\text{-}fall}$ decreases during protogalactic collapse. When the ratio $\mathscr{R}$ drops to unity, gas starts to condense out (Fall & Rees 1985); the density of the hot phase is thereby reduced until it can no longer cool within the free-fall time-scale. If the gas is sufficiently inhomogeneous, of course, clouds can exist even when this ratio is larger: cooling flows exemplify this possibility.

It is from the cool-phase gas (with $T \lesssim 10^4$ K) that stars would form: clouds massive enough, or dense enough, to be Jeans-unstable would contract, initiating star formation inside them. Instability would be triggered by a build-up of the pressure of the confining (hot-phase) medium during the collapse of the protogalaxy; also, clouds may grow by coalescence. The clouds would be expected to form with a broad spectrum of sizes, stretching well below the threshold for Jeans instability; different-sized clouds would therefore become unstable at different stages of protogalactic collapse. Even if the star formation in each cloud were rapid and efficient once it became Jeans-unstable, the overall conversion of protogalactic gas into clouds would take at least as long as the overall contraction of the protogalaxy. If the mass distribution in the halo of the protogalaxy can be modelled as an isothermal sphere with velocity dispersion V_c, then the free-fall time from a radius 50 r_{50} kpc is $t_{\text{free-fall}} = 3 \times 10^8\ r_{50}\ (V_c/200\ \text{km s}^{-1})^{-1}$ yr.

3 The effect of radio lobe production

How, then, is star formation in a two-phase gas affected if the galaxy becomes a strong radio source? When a central object starts to generate a relativistic directed outflow, shocks advance with speed $\gg V_{\text{virial}}$, inflating double radio lobes whose internal pressure greatly exceeds the gas pressure outside. Typical speeds for the advance of the head of the source are 0.1 c; even the transverse expansion of the cocoon around the jet could be highly supersonic with respect to external 'hot phase' material. The internal pressure in a radio source, in the form of relativistic particles and magnetic fields, is minimized by the equipartition assumption. In the lobes of 3C 368, the equipartition field is 3×10^{-4} G, the corresponding minimum pressure being 10^{-8} dyn cm^{-2} (Djorgovski *et al.* 1987). General estimates are unlikely to be lower than 10^{-10} dyn cm^{-2}.

In their discussion of an isolated protogalaxy, Fall & Rees (1985) assumed the hot-phase gas to be at a temperature such that the sound speed equalled V_c for the postulated isothermal halo, and that it had a density such that $\mathscr{R} = 1$. This assumption yields an external density 0.02 r_{50}^{-1} cm^{-3}, and a pressure $10^{-11}\ r_{50}^{-1}$ dyn cm^{-2}. (These figures correspond to $V_c = 200$ km s^{-1} and scale roughly as V_c^2 and V_c^4, respectively.) The pressure boost resulting from the radio activity is therefore at least 100, and may be as much as 10^4 for the hotspots. This implies, irrespective of the detailed model, that the boundaries of a radio lobe would advance with a Mach number $\mathscr{M} \simeq 10$–100 into the external medium.

Were this external medium exclusively in the hot phase (with $T \simeq T_{\text{virial}}$), the prime effect of the radio outburst would be to *inhibit* star formation, by evacuating the radio lobe of thermal gas, and raising the surrounding medium (via shock heating) on to such a high adiabat that it could never cool. However, it is the denser cool-phase clouds (filling a small fraction of the volume) which are more directly relevant to star formation. the shock would essentially *bypass* these clouds, leaving them in an overpressured environment which triggers many of them to collapse.

The momentum imparted to a cloud (*cf.* McKee & Ostriker 1977) would be the post-shock pressure multiplied by the time it takes for the shock in the surrounding medium to pass it by. (It is only for this brief period that the front and back of the cloud experience very different pressures.) This speed is easily shown to be independent of cloud size; for clouds of temperature T_c in pressure balance with gas at T_{virial}, it is $\mathscr{M}(T_c/T_{\text{virial}})\ V_{\text{virial}}$. The temperature ratio in this expression is typically $\lesssim 10^{-2}$, which implies that pre-existing clouds would not reach the escape velocity even if they were directly shocked by the jet.* moreover, clouds would survive the impulse, the internal shocks passing through them being sufficiently weak that they cool without disrupting.

After the shock has passed, the clouds find themselves overpressured by a factor of $\sim\mathscr{M}^2$. The value of $\mathscr{M}$ may be ~ 100 along the jet, and ~ 10 for the transverse expansion of the cocoon (where the inferred internal pressure is typically 100 times less than in the hotspots). The resultant overpressure would trigger collapse of all clouds down to a fraction 0.01–0.1 of the previous Jeans mass, resulting in a well-synchronized burst of star formation, at a rate enhanced by a factor of the order of $\mathscr{M}$. To quantify this further, one would need to model the distribution of cloud masses. There is a lower limit set by thermal conduction. But for any broad mass spectrum, sudden reduction in the Jeans mass by 10–100 would trigger collapse of a substantial fraction of the cool-phase gas. So the short-lived population could be enhanced up to 100-fold, even if the *form* of the IMF were in no way altered. (If the radio-source environment altered the IMF in a distinctive way, the enhancement could of course be larger still. The orbits of the resultant population could retain, for the entire lifetime of the galaxy, some memory of the radio alignment.)

4 Discussion

The foregoing considerations are independent of whether there is an underlying older population as advocated by Lilly (1989), or whether the colours can be made consistent with a young high-mass population (Chambers *et al.* 1988a; Bithell, in preparation). If Lilly is right, there is no evading the conclusion that the high-z radio galaxies are massive; moreover, they must then have formed at much higher redshifts than those they are observed at. This is an important issue for models of galaxy formation. Large numbers of massive galaxies at the observed high redshifts (even very young ones) would pose a problem for some cosmogonic schemes; galaxies with $z=3$ that were already $1-3\times10^9$ yr old would seem an embarrassment for almost all theories. In modelling the colours we must also bear in mind that the optical luminosity may be augmented by emission from the gas clouds, and by non-thermal continuum [either scattered from the nucleus (Fabian 1989) or radiated within the extended lobes themselves].

Although I have referred simply to 'clouds', nothing in the foregoing discussion is sensitive to the configuration of the cool gas – whether it is spherical clouds, filaments, or sheets. Some evidence for 'clumping' of gas comes from the Faraday depolarization data of Pedelty *et al.* (1989). These data have the further implication that $\sim 10^{-5}$ G magnetic fields must pervade the 'clouds'. Pre-existing fields would have been amplified by compression during protogalactic contraction, and been strengthened by a further factor of ~ 100 during the compression of cool-phase clouds. If, alternatively, the magnetic flux were generated in the radio lobe, it must have had time to diffuse into the clouds via finite-conductivity effects.

The triggering effect would be less conspicuous in lower z radio sources. At early epochs, most of the baryonic mass of a galaxy would still be gaseous (some in clouds); less gas would

*Emission lines in, for instance, 3C 321.6 (McCarthy *et al.* 1987a) suggest gas velocities up to 1000 km s^{-1}. This could be outflow along the part of the jet with highest momentum density. However, it is worth noting that spurious apparent velocities, at least in the Lyman lines, could arise from repeated scattering in a contracting/expanding medium (Bonilha *et al.* 1979; Rybicki, private communication). Multiply scattered photons would systematically gain/lose energy in a contracting/expanding medium, emerging preferentially in the blue/red wing. For column densities of 10^{21} cm^{-2}, these shifts could mimic velocities of 1000 km s^{-1}. We are a long way from disentangling the kinematics in these systems.

survive at later epochs, though galaxies embedded in 'cooling flows' might still display analogous effects at a lower level. It is worth recalling another significant difference between high- and low-z radio galaxies, pointed out by Barthel & Miley (1988). At high redshifts, sources are much less symmetric than low-z sources of similar radio power, which provides independent corroboration that the gaseous environment is denser and more disturbed around the more distant sources.

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