IAU Colloquium 164: Radio Emission from Galactic and Extragalactic Compact Sources
ASP Conference Series, Vol. 144, 1998
J. A. Zensus, G. B. Taylor, & J. M. Wrobel (eds.)

The Ultimate Fate of CSOs

D. S. De Young
Kitt Peak National Observatory, Tucson, AZ 85719, U.S.A.

Abstract. Recently Readhead et al. (1996b) have presented empirical evidence that CSOs evolve into larger double sources many kpc in extent. The implications of this are explored analytically and numerically. It is found that pure luminosity evolution on the small scales of CSOs is unlikely in the presence of any ambient density gradients. However, the transition from CSO to MSO may involve a nearly constant lobe advance speed as suggested by Readhead et al.. This seemingly unphysical result can be seen to result from the interaction of the propagating jet with its surrounding medium.

1. The Evolution of CSOs

The idea of "ram pressure confinement" was introduced into the early radio source literature (De Young & Axford 1967) in order to overcome the morphological difficulties encountered by the notion of inertial confinement of extragalactic radio sources. For a jet of constant thrust, as assumed by Readhead et al., under the assumption of ram pressure confinement the energy density in the hot spot is related to the external medium by $\epsilon = \rho_e {v_a}^2$, where ρ_e is the ambient gas density and v_a is the advance speed of the the hot spot. For a constant jet input v_a is proportional to $\rho_e^{-1/2}$, not at all independent of the external density. However, this purely local condition does not include important physical processes occurring in the rest of the radio source, especially its interaction with the surrounding medium. For example, in creating the radio lobe, $dE/dt = 0 = \dot{E}_{jet} - p_e dV/dt$, where $\dot{E}_{jet}$ is the total energy flux of the jet and is assumed to be constant. Then if ϵ is the energy density in the expanding radio source $d\epsilon/dt = (1/V)dE/dt - (E/V^2)dV/dt = (-\epsilon/V)dV/dt$. But as $dV/dt = \dot{E}_{jet}/p_e$, the above equation integrates to the simple form $\epsilon = \epsilon_o(t/t_o)^{-1}$. Employing the local ram pressure condition $\epsilon = \rho_e {v_a}^2$, one has $\rho_e {v_a}^2 = \epsilon_o t_o/t$. Implicit in this is the assumption that v_a is much greater than the sound speed in the external medium and that ϵ is uniform inside the source. If one now sets a restriction that $v_a = constant$, then t is simply given by $t = R/v_a$, where R is the location of the leading edge of the hot spot. Solving the ram pressure equation for ρ_e then gives $\rho_e = (\epsilon_o t_o/v_a)(1/R)$.

Thus the simple treatment above implies that setting the hot spot advance speed equal to a constant implies that the ambient density must decrease as R^{-1}, which is remarkably similar to the relation $\rho_e \propto R^{-1.3}$ deduced empirically from the data by Readhead et al. The immediate conclusion that can be drawn from this is that more physics needs to be included than is found in the purely local ram pressure confinement relation.

2. Numerical Simulations

To further determine the evolutionary characteristics of CSOs a series of numerical simulations was made with jet propagation into differing environments. The calculations are two-dimensional and axisymmetric, and the jet properties were taken from the data on CSO 2352+495 (Readhead et al. 1996a).

The results for the CSO propagation over the inner 300 pc reveal nothing unexpected. Hot spot propagation for an ambient number density of 10 shows some jet deceleration, though the jet velocity is rather constant during the later stages. The average jet speed over this period is $0.024c$, which is very close to that deduced by Readhead et al. for CSOs of this size. The jet propagation depends dramatically on the ambient density, with the jet moving more rapidly in less dense regions and accelerating down a density gradient.

The calculation of possible evolution of CSOs into MSOs provides more interesting and less intuitive results. For propagation of a jet into a constant density medium over 2 kpc the hot spot clearly decelerates, even though the jet thrust is constant and the medium is homogeneous. The average hot spot advance speed in this case is $0.003c$, well below the $0.02c$ suggested by Readhead et al. The results for hot spot propagation into an ISM whose density declines as $R^{-1.3}$, which is the empirical relation found by Readhead et al., shows a remarkable result, namely that the hot spot advance speed over distances of 3 kpc *is* approximately constant. Moreover, the average hot spot advance speed in this calculation is $0.018c$, which is again very close to the value of $0.02c$ put forward in the empirical model.

At first appearance these results may seem counterintuitive. However, energy flows into the hot spot and powers its advance only after it has propagated all the way out from the nucleus. Along the way there are energy and momentum losses in the jet that occur in the mixing layer that separates the jet from its environment. This process mass loads the jet and will decelerate it over long distances. For a jet moving into a decreasing density gradient it is clear that the steepness of the gradient can be made to just compensate for the boundary losses along the jet so that the tendency for jets to accelerate into decreasing density gradients can balance the momentum losses due to mass entrainment and mixing.

These preliminary calculations imply that a roughly constant entrainment rate per unit length along most of the jet may not be a bad first approximation, but a much more detailed and physically motivated model needs to be developed. Finally, these results show that for the jet energy densities applicable to luminous CSOs such as 2352+495, CSOs are probably not "frustrated and confined" but instead can evolve into larger objects such as MSOs and LSOs.

References

De Young, D. S., & Axford, W. I. 1967. *Nature*, **216**, 129–131.

Readhead, A. C. S., et al. 1996a. *ApJ*, **460**, 612–633.

Readhead, A. C. S., et al. 1996b. *ApJ*, **460**, 634–643.