EMISSION LINES: SIGN OF A NEW ENERGY SOURCE?

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In addition to the occurrence of emission line regions coexistent with extended radio sources which have been discussed at this Symposium, this phenomenon has been observed earlier in 3C277.3 (Miley et al. 1981) and in Centaurus A (Graham and Price 1981). This gas has been detected only in the Fanaroff and Riley "Class I" radio sources. Data concerning this class of object suggest that outflow from the nucleus is proceeding at transonic or subsonic speeds and this correlation has led to the suggestion (De Young 1981) that the origin of the emission line gas arises from entrainment of the interstellar medium into the ejected material.

Discussion of the entrainment process and a calculation of the entrainment rate are found in De Young (1981), and good agreement is obtained with the observations of Cen A and 3C277.3. What is discussed here are further observations and developments concerning this idea. It is encouraging that the new observations of 4C26.42 reported here (Heckman and van Breugel, this volume) not only find emission lines coincident with an extended radio source, but also that there appears to be an enhancement of the line emission around the periphery of the radio source. This is an expected result of boundary layer entrainment.

Entrained interstellar gas will have first been heated by the shock front produced by passage of the initial stream of material ejected from the nucleus. A jet velocity of $\sim 10^3$km s^{-1} will heat this gas to $\sim 10^7$K, and it will cool to emission line temperatures in $\gtrsim 2\times10^6/n$ yr, where n is the number density. Recent x-ray data may give some evidence for this cooling process. Miley, Norman, and Silk (1981) have detected an x-ray flux of $\gtrsim 1.2\times10^{43}$erg s^{-1} from 3C277.3 (Coma A). In addition an extended x-ray source has been observed coincident with the emission line radio galaxy 3C305, and these data provide a limit on the mass of the x-ray emitting gas of $n_e M_X \leq 3\times10^8 M_\odot$ cm^{-3} for $T \leq 10^{7.5}$K (Heckman 1981, private communication). This mass limit is consistent with the results of the earlier entrainment calculations which yield 6×10^7 - 6×10^6 $M_\odot$ entrained over 10^8 yr for ambient number densities in the range 0.1-0.01 cm^{-3}.

As the line emitting gas cools further, star formation can occur,

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and in fact Graham and Price (1981) have observed at least 10^2 young massive ($\sim 10 M_\odot$) stars in the northeast radio lobe of Cen A. For Cen A and Coma A the Jeans masses and lengths at 10^2 K vary from $\sim(10^4-10^2) M_\odot$ and $\sim(10^2-1)$pc, using the observed limits on the number density. Collapse times vary from 10^5 to 10^7 years. The mass function for star formation in such an environment is unknown, but if a Salpeter function is used with cutoffs of 30 and 0.1 $M_\odot$ then 10^4-10^5 stars of mass greater than $10 M_\odot$ could be formed over 10^8 yr, assuming 10% efficiency.

The key point is that these stars are made of gas entrained by the outflow and thus also move outward. At the end of their lifetime ($\sim 10^7$ yr) these massive stars will explode and inject $10^{51}-10^{52}$ erg per star into the surrounding gas. In addition an outward moving remnant is left which can provide $\sim 10^{38}$ erg s^{-1}. It has been known for some time that the Class I radio sources very often require energy replenishment before the outflow reaches the extremities of the radio source as well as in the more distant regions themselves. The supernovae and supernova remnants due to the evolution of massive outwardly moving stars may be a significant source of the required energy. After the first 10^7 years the remnants alone can inject 10^{41} ergs s^{-1}, and ten times this value at the presumed current age of $\sim 10^8$ yr. Also possible is the formation of more massive objects whose evolutionary end point is a black hole, thus providing a more efficient source of energy within the radio source.

A supernova will not disrupt the outflow, since the radius of the remnant is ~ 50 pc for $E_{sn} = 10^{51}$ ergs and $n = 10^{-2}$ (Chevalier 1974) which is much smaller than the size of the beam or bridge. For $n \sim 10^{-2}$ radiative losses are less important than the kinetic energy which will "stir" the outflow as well as provide a source of stochastic reacceleration of the electrons. Bright knots are commonly observed along the bridges of Class I radio sources, and the location of these knots close to the parent galaxy suggests that they might arise from the local stirring of the outflow due to one or more supernovae. Entrainment occurs principally near the onset of the turbulent boundary layer, well inside the galaxy. In a "mature" radio source the ISM near the outflow will have cooled from its original post-shock temperature. Entrainment of this gas can lead to early star formation, especially if any inhomogeneities are present, and with a lifetime of $\sim 10^7$ yr a massive star will have traveled only a few tens of kiloparsecs before a supernova occurs.

References

Chevalier, R.A. 1974, Ap.J., 188, 501.
De Young, D.S. 1981, Nature, 293, 43.
Graham, J.A., and Price, R.M. 1981, Ap.J., 274, 813.
Miley, G.K., Heckman, T.M., Butcher, H.R. and van Breugel, W.J. 1981, Ap.J. Lett, 247, L5.
Miley, G.K., Norman, C., and Silk, J. 1981, in preparation.