EXTENDED OPTICAL LINE EMISSION ASSOCIATED WITH RADIO GALAXIES

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I. INTRODUCTION

Using the Video Camera (e.g. Butcher et al. 1980) and the High Gain Video Spectrometer (e.g. Heckman et al. 1981) we are carrying out a program at Kitt Peak to search for optical line emission associated with the jets and lobes of radio galaxies. Several sources have been found in which extended optical line emission is clearly related to the non-thermal radio emission. Some general information on these and a few other sources is summarized in Table 1.

TABLE 1

Source	Redshift	Radio Luminosity (10^{42}erg s^{-1})	Absolute Optical Magnitude	Galaxy Morphology	References
3C 277.3	.0857	7.3	-21.8	E	Miley et al. 1981
3C 293	.0450	2.3	-22.6	peculiar	---
3C 305	.0410	1.3	-22.4	peculiar	Heckman et al. 1981
M87	.0043	1.1	-21.6	E	Ford & Butcher 1979
4C 29.30	.0650	0.9	-22.4	peculiar	van Breugel et al. 1981
4C 26.42	.0630	0.7	-23.2	CD	" "
NGC 7385	.0259	0.5	-20.5	E	Simkin & Ekers 1979
Cen A	.0016	0.1	-21.5	peculiar	Graham & Price 1981

Our optical imaging and spectroscopic data combined with accurate VLA maps of comparable resolution (∿1") allow some preliminary, general conclusions to be made. We will briefly discuss these and illustrate several points using 4C 26.42 (Figure 1) and 4C 29.30 (Figure 2).

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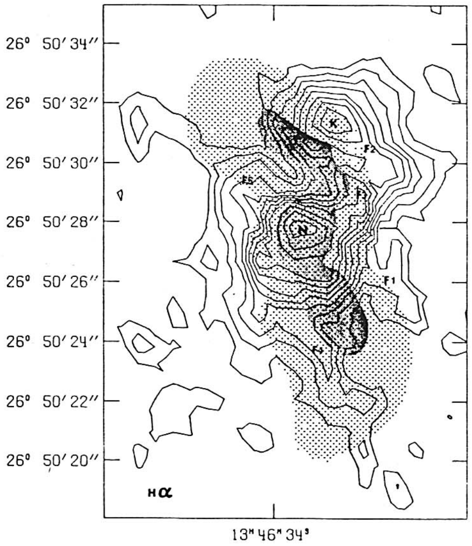
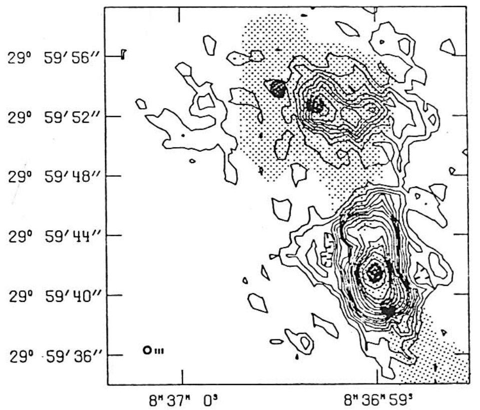
II. OBSERVATIONAL RESULTS

Figure 1



4C 26.42

Figure 2



4C 29.30 (part)

Contours represent optical line emission (Hα and OIII respectively). Shaded areas outline the radio sources, dark regions indicate radio brightness enhancements.

1. The optical line emission is predominantly found along the radio source boundaries. This particularly clear for 4C 26.42.
2. The optical line emission is usually brightest near, but slightly offset from, bright radio knots or hotspots. At these locations the radio source (jet) often deflects, the optical emission line 'knot' being near the outer bend.
3. Generally the radio source is nearly entirely depolarized at 6 cm at locations where the optical line emission overlaps with that of the radio source.
4. In the two cases where we have adequate spectroscopic data (3C 305, 3C 277.3) the pressures in the line regions are comparable to those in the radio source, granted the usual assumptions.
5. The bulk velocities of the gas in the emission line regions are typically 200-300 km s^{-1} and the velocity widths 300-500 km s^{-1}.
6. Several of the galaxies are peculiar i.e. they have spiral arm like structure, disks, dust lanes. Others however appear to be 'normal' ellipticals. All radio galaxies have relatively low radio luminosities but their associated galaxies are relatively bright.
7. Although in general the line emitting regions are located within the parent galaxies, there are cases such as 3C 277.3 and Cen A where line emission is detected as far out as 40 kpc from the galaxy nucleus.

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III. PRELIMINARY DEDUCTIONS

Origin of the line emitting gas.

One can envisage the following possible origins for the line emitting gas: a) it exists 'in situ', b) it is transported outwards or c) it is falling in. Although it is difficult to observationally discriminate between these possibilities, there is circumstantial evidence that all of these can occur.

a) In 4C 29.30 the northern emission line region is located in a region of a spiral arm like structure in the galaxy. At the same position the radio source flares up and deflects. This is suggestive of a jet interacting with a locally dense environment. Similarly, our optical data indicate the presence of rapidly rotating gaseous disks in the core regions (a few kpc) of several of the other galaxies in Table 1. In all these cases, and presumably also in the core of 4C 29.30, there are strong indications based on the morphologies of the radio and optical line emission that jets are interacting with locally dense gaseous environments.

b) There is indirect evidence in some cases (Cen A, 3C 305) for outflow of the emission line gas consistent with the outflow which seems to occur on a much smaller scale in other active galaxies (Heckman et al. 1981 (II)).

c) In M87 as well as in other giant galaxies with dense gaseous (X-ray) halo's such as NGC 1275, it is generally argued that emission line filaments are formed as a result of radiatively regulated accretion of gas onto the massive central object (e.g. Cowie and Binney, 1977; Fabian and Nulsen, 1977). This might also be the case in 4C 26.42 which is identified with a cD galaxy in A 1795, a bright X-ray cluster (e.g. Perrenod and Henry, 1981).

Exitation mechanisms.

In only a few cases is sufficient spectroscopic data available to discriminate between various possible exitation mechanisms such as for example: a) photo-ionization, b) shockheating. As with the origin of the gas, it appears that different mechanisms may occur in different sources. For example in 3C 277.3 photo-ionization seems to be the most plausible process responsible for the optical line emission associated with the jet. In 3C 305 the situation is rather complex and both photo-ionization as well as shock-heating may occur. The probable occurrence of radiatively regulated accretion onto massive galaxies has already been mentioned above. In this picture the emission-line gas is excited by re-pressurizing shocks driven by the hot surrounding gas.

Depolarization mechanisms.

The preferential occurence of line emitting gas at the boundaries of radio galaxies may have profound implications for the interpretation

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of radio (de-)polarization measurements. For example the enhanced emission line brightness alongside 4C 26.42 is most readily interpreted as being due to a line of sight effect of a thin layer of ionized gas surrounding the radio source. It is very likely that this gas is clumpy on a scale much smaller than the observing beam (<<1" or 1 kpc). The very low percentage polarization at 6 cm and i.e. the absence of highly polarized boundaries is in clear contrast to what is usually observed (see for example van Breugel, 1980). Thus it seems that 4C 26.42 is being depolarized by a 'screen' of clumpy, magneto-ionic thermal gas which is mixed in with the outer layers of the radio source. In this case the radio emission depolarizes more quickly and at shorter wavelengths than in the (usually assumed) case of the ionized gas being mixed throughout the radio-emitting regions (see Burn, 1966).

Powering the radio sources.

Within the context of the usual assumptions (such as minimum energy etc), the relatively low bulk velocities of the emission line gas pose problems for radio source models in which it is assumed that a) the radio source is powered by a jet of large bulk kinetic energy and that b) the observed velocities are representative of the velocities in such a jet. To supply the minimum required energy, with 100% conversion efficiency, to power a source like 3C 277.3, implausibly high gas densities (>10 cm^{-3}) and mass loss rates (>10 $M_{\odot}$ yr^{-1}) would be required. Clearly however, a velocity gradient across a jet may exist and in cases where outflow of the emission line gas is favoured, one may argue that the observed velocities are merely those existing in the outer (entrainment ?) layers of the jet.

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