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Emission Lines from Jet Flows (Isla Mujeres, Q.R., México, November 13-17, 2000)
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THE EMISSION LINE REGIONS OF REDSHIFT ONE RADIO GALAXIES

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RESUMEN

Hacemos una reseña de las ideas corrientes sobre las zonas emisoras de líneas en radio galaxias con corrimientos al rojo de $z \sim 1$. Primero, consideramos la evolución de las propiedades del gas emisor de líneas desde el universo cercano hasta $z \sim 1$. Luego, consideramos el origen de la ionización y de los estados cinemáticos del gas en poderosas galaxias 3CR a $z \sim 1$, y en particular mostramos que éstas evolucionan fuertemente a lo largo de la vida de la radio fuente como resultado del profundo efecto del pasaje de choques a través del medio interestelar de la galaxia. Demostramos que esta dicotomía persiste a z más bajo y también en una muestra de radio galaxias de menor potencia al mismo z. Finalmente, discutimos las implicaciones de estos resultados para el entendimiento de las propiedades del gas emisor de líneas y del papel más amplio de las interacciones jet/nube.

ABSTRACT

We review the current understanding of the emission line regions in radio galaxies at redshifts $z \sim 1$. First, we consider the evolution of the emission line gas properties from the nearby Universe out to $z \sim 1$. Next, we consider the origin of the ionization and kinematical states of the gas in powerful 3CR radio galaxies at $z \sim 1$, and in particular show that these evolve very strongly through the lifetime of the radio source due to the profound effect of the passage of the radio source shocks through the interstellar medium of the host galaxy. We show that this dichotomy persists at lower redshifts and also in a lower radio power sample of radio galaxies at the same redshift. We discuss the implications of these results for understanding the nature of the emission line gas and the broader role of jet-cloud interactions.

Key Words: **GALAXIES: ACTIVE — GALAXIES: ISM — RADIO CONTINUUM: GALAXIES — SHOCK WAVES**

1. INTRODUCTION

The emission line properties of powerful distant ($z \gtrsim 0.5$) radio galaxies are remarkable. Their emission line luminosities are large, with the rest-frame equivalent width of the [O II] 3727 line increasing with redshift to 100 Å or even more by redshifts $z \sim 1$ (e.g., Baum & McCarthy 2000). Although at low redshifts the emission line regions are (with some noteable exceptions) rarely much larger than the giant elliptical galaxy which hosts the radio source, by redshifts $z \gtrsim 0.3$ they are almost invariably spatially extended over regions that can be as large as 100 kpc, and are frequently elongated along the direction of the radio axis (e.g., McCarthy, Spinrad, & van Breugel 1995). This is known as the alignment effect.

The source of ionization of this gas has been a long standing question. Robinson et al. (1987) found that optical emission line spectra of most low redshift ($z \lesssim 0.1$) radio galaxies are well explained using photoionization models, and a similar result was found for a composite spectrum of radio galaxies with redshifts $0.1 < z < 3$ (McCarthy 1993). Photoionization models are also supported by orientation-based unification schemes of radio galaxies and radio-loud quasars (e.g., Barthel 1989), in which all radio galaxies host an obscured quasar nucleus (AGN): the flux of ionizing photons required to produce the observed luminosities of the emission line regions can be shown to be comparable to that produced by radio-loud quasars at the same redshift (McCarthy 1993 and references therein). On the other hand, detailed studies of individual sources (e.g., 3C171; Clark et al. 1998) show dramatic variations in the ionization state close to the radio hotspots, with the ionization state of the gas in these regions being consistent with that expected from shock ionization (see also Villar-Martín et al. 1999a). The relative importance of shocks and photoionization in producing the emission line properties of the general radio galaxy population therefore remains an open question.

The kinematics of the emission line gas are equally striking. At low redshifts a variety of kinematical states of the emission line gas are seen, from galaxies whose gas has a smooth velocity profile consistent with simple rotation and low full-width at half-maximum (FWHM; up to a couple of hun-

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dred $\mathrm{km\,s^{-1}}$) through to those galaxies classified as 'violent non-rotators' with large turbulent velocity structure and FWHM up to $\sim 500\,\mathrm{km\,s^{-1}}$ (e.g., Baum, Heckman, & van Breugel 1992 and references therein). Sources such as 3C171 (see above) also show extreme gas kinematics close to the radio hot-spots, indicative of acceleration by radio source shocks. At higher redshifts ($z \gtrsim 0.6$), it is common to find radio galaxies whose emission line gas has FWHM in excess of 1000 $\mathrm{km\,s^{-1}}$, and large velocity shears across the emission line regions (e.g., McCarthy et al. 1995; Baum & McCarthy 2000). The exceptional nature of these kinematics has been reinforced by more detailed studies of individual sources (e.g., Tadhunter 1991; Meisenheimer & Hippelein 1992; Hippelein & Meisenheimer 1992; Stockton, Ridgway, & Kellogg 1996; Neeser et al. 1997).

In this paper we review the recent work that has been carried out to address important issues related to the emission line gas regions around redshift $z \sim 1$ radio galaxies. In particular:

- What is the relative importance of the AGN and radio source shocks in ionizing the emission line gas?
- How big a role do radio source shocks play in giving rise to the observed kinematics?
- Why are there such large differences in the emission line gas around low and high redshift sources?
- How do the properties of the interactions vary with the power of the radio jets?
- In what other aspects of radio source astrophysics are jet-cloud interactions important?

In §§ 2 and 3 we describe the ionization and kinematic results respectively of a spectroscopic program (Best et al 2000a,b) to observe a sample of the most powerful radio galaxies at redshifts $0.7 < z < 1.25$. These sources are drawn from the revised 3CR radio catalogue, which comprises the brightest sources in the northern sky selected at 178 MHz (Laing, Riley, & Longair 1983). A comparison of the results of this work with those at low redshift is presented in § 4. In § 5 we present some results (Inskip et al. in prep.) from equivalent observations on a matched sample of galaxies drawn from the 6C radio catalogue, a factor of 6 lower in radio luminosity, to investigate the effects of radio source power. The results are discussed in § 6, and our conclusions drawn in § 7.

2. THE IONIZATION OF $z \sim 1$ RADIO GALAXIES

Best et al. (2000a,b) have made deep long-slit spectroscopic observations with the William Herschel Telescope of a sample of 14 radio galaxies with redshifts $0.7 < z < 1.25$. The dual-beam ISIS spectrograph provided a wide wavelength coverage and allowed an investigation of emission line ratios from the rest-frame ultra-violet to longward of the 4000 Å break. The line ratios of C III] 1909 / C II] 2326 and [Ne III] 3869 / [Ne V] 3426 were determined for these galaxies. These line ratios are particularly useful for ionization studies for three reasons: (i) in both cases the two lines in the ratio involve the same element, and so variations in metallicity or abundance are not important; (ii) the two lines are very close in wavelength, and so differential extinction is minimised; (iii) the theoretical predictions of photoionization and ionization by shocks for these line ratios are very different.

Theoretical predictions for these line ratios for photoionization models were taken from Allen et al. (1998), generated from the MAPPINGS II code (e.g., Sutherland et al. 1993) assuming illumination of a planar slab of gas by a power-law ($\alpha = -1.0$ or $\alpha = -1.4$) spectrum for a range of ionization parameters and two different gas densities ($n = 100$ or $1000\,\mathrm{cm^{-3}}$). Shock ionization predictions were derived from the models of Dopita & Sutherland (1996), varying the shock velocity (150 to $500\,\mathrm{km\,s^{-1}}$) and the 'magnetic parameter' ($0 \leq B/\sqrt{n} \leq 4\,\mu\mathrm{G\,cm^{-1.5}}$, where n is the number density). The line ratios were calculated both for the shocked gas, and for the combination of shocked gas with a precursor region, the latter corresponding to emission from the pre-shock gas due to ionizing photons produced by the shock diffusing upstream ahead of the shock front (see Dopita and Sutherland 1996 for further discussion). These models are discussed in Best et al (2000b).

The observed line ratios are compared with the theoretical predictions on Figure 1. Four 3CR galaxies (3C217, 3C324, 3C352, 3C368) lie in the region of the diagram occupied by shock models, and five (3C22, 3C265, 3C280, 3C340, 3C356) lie close to the photoionization predictions. Interestingly, the four sources in the shock region have radio sizes smaller than 115 kpc ($\Omega = 1$, $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$), and the five 'photoionized sources' have larger radio sizes. This is clearer in Figure 2; there is a strong (98.5% significant) correlation between the C III] 1909 / C II] 2326 ratio and the radio size. The sources whose radio size is within about a factor

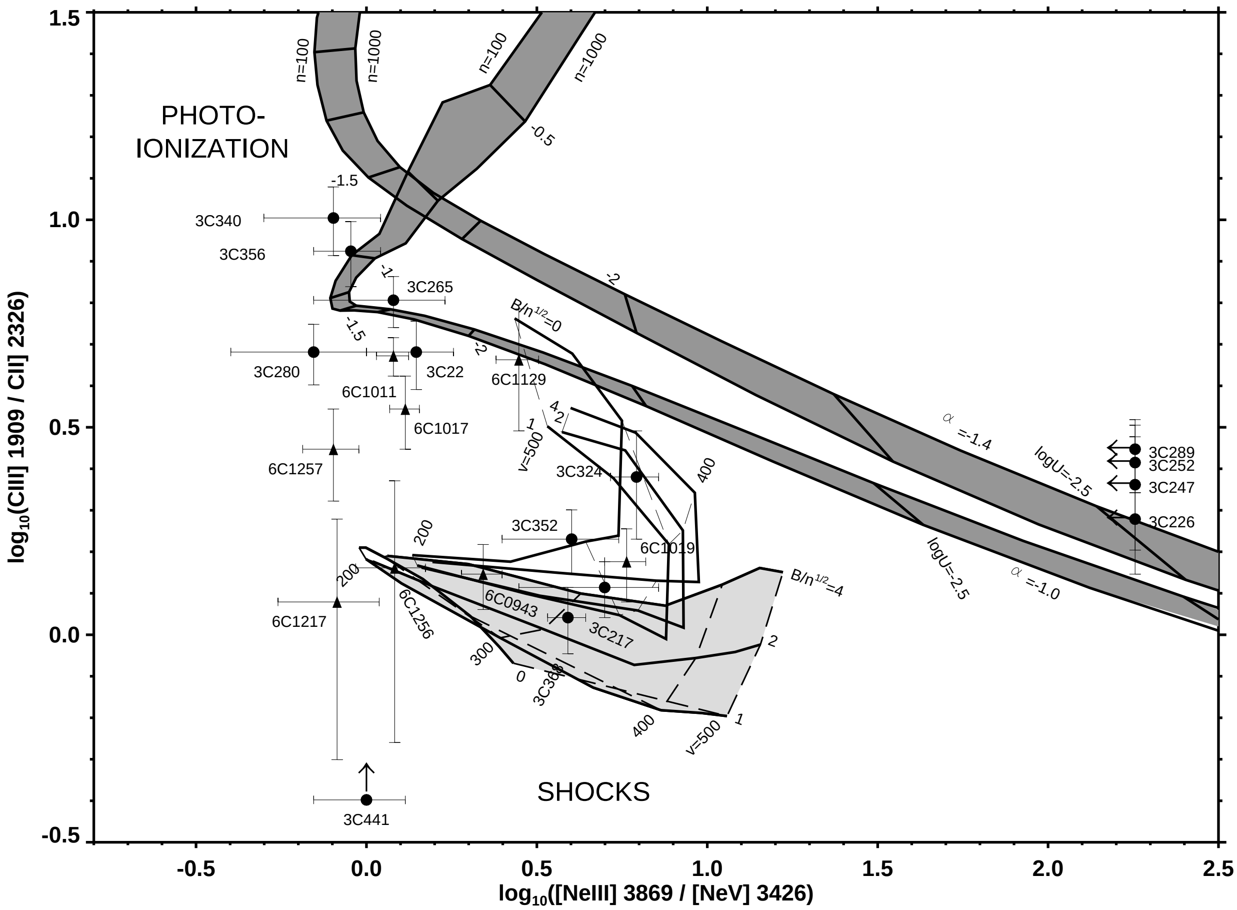

Fig. 1. Emission line ratios for the 3CR (circles) and 6C (triangles) radio galaxies, compared with theoretical predictions of photoionization (upper shaded regions), shock ionization (lower shaded regions), and shock ionization including a precursor region (unshaded line region). For the five 3CR galaxies at the edges of the plot, no data is available for one of their line ratios. Note that the 3CR sources split into two populations, one (3C217, 3C324, 3C352, 3C368) with the ratios expected for shock ionization and one (3C22, 3C265, 3C280, 3C340, 3C356) close to the photoionization models. Interestingly it is all of the small sources which are consistent with shock ionization. The behaviour of the 6C sources is, in general, the same, although the bimodality is less pronounced.

of two of the size of the emission line region show lower ionization states than expected for photoionization, suggesting an interpretation whereby the radio source shocks strongly influence the ionization state of the emission line gas as they pass through the host galaxy. This interpretation is supported by kinematical differences, as considered in the next section.

3. KINEMATICAL PROPERTIES

Many kinematical properties of the emission line gas are also found to evolve strongly with the size of the radio source. The FWHM of the [O II] 3727 emission is plotted against radio size in Figure 3, and shows a strong anticorrelation. Similarly, if the velocity profile along the slit of the emission line gas is classified into two categories, those consistent with rotation and those with distorted profiles ($N_{\rm v} = 1$ and $N_{\rm v} > 1$ respectively: see Best et al. 2000b for details) then it is found that there is a $> 99\%$ significant difference in radio size distributions between the two classes (Figure 4); the small sources have more distorted profiles. Both of these results are consistent with the emission line gas in small radio sources being disturbed by the passage of the radio source shocks passing through the interstellar and intergalactic medium.

It is not only the kinematics of the gas that evolve with the radio source size, but also the physical extent and the luminosity of the line emission. Figure 5 shows the variation of the equivalent width

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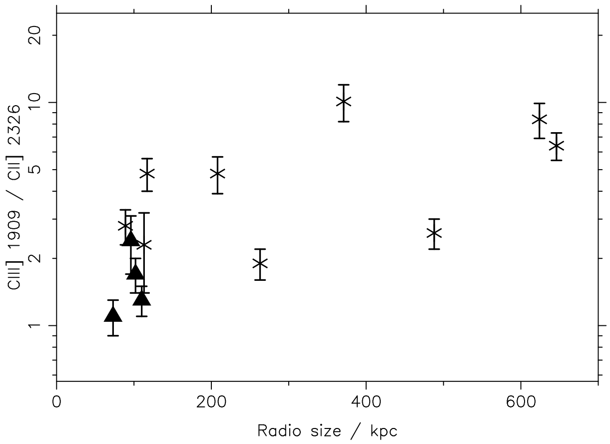

Fig. 2. The correlation between the C III] 2326/C II] 1909 emission line ratio and the projected linear size of the radio source. The four sources lying in the 'shocks' region of the line diagnostic diagram, Figure 1, are plotted as filled triangles and the remainder of the galaxies as asterisks.

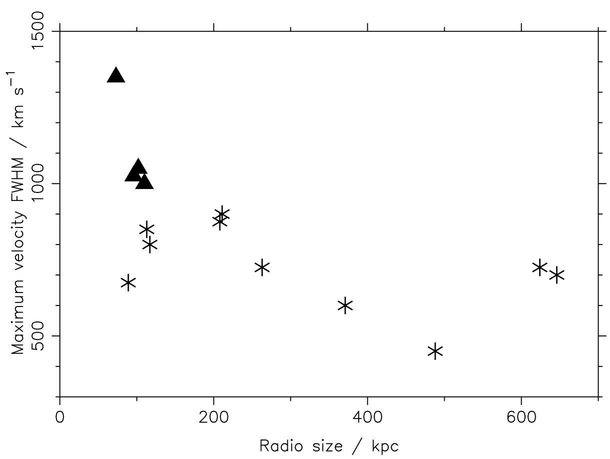

Fig. 3. The inverse correlation between the maximum FWHM of the [O II] 3727 emission line and the projected linear size of the radio source. Symbols as in Figure 2.

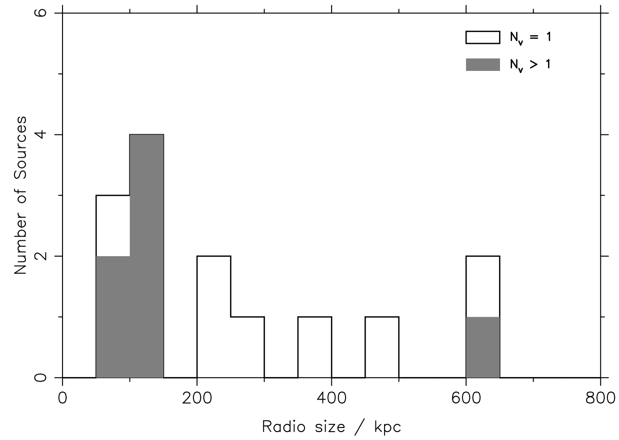

Fig. 4. A histogram of the radio size distribution of the sources, separated into sources with smooth velocity profiles ($N_\mathrm{v} = 1$, unshaded) and those whose profiles are irregular ($N_\mathrm{v} > 1$, shaded).

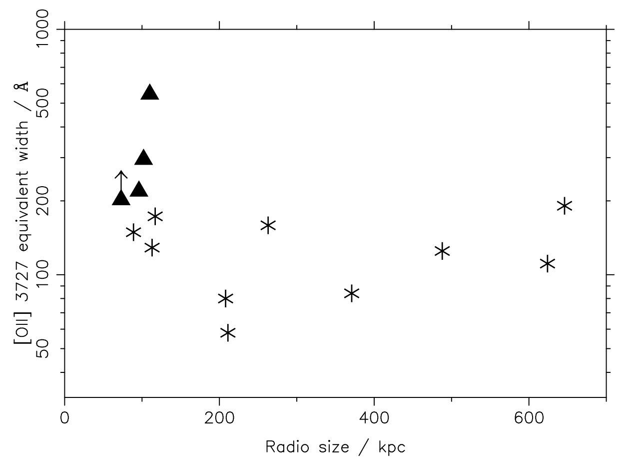

Fig. 5. The decrease in the equivalent width of the [O II] 3727 emission line with increasing size of the radio source. Symbols as in Figure 2. 3C368 is plotted as a lower limit due to the contribution of the M-star to its continuum level.

of the [O II] 3727 emission line with increasing size of the radio source. Although this correlation is less strong (96% significance in a Spearmann Rank test), it is apparent that the small sources in the 'shock-dominated' region of Fig. 1 show enhanced [O II] 3727 equivalent widths. A more accurate description of Fig. 5 is not that there is an inverse correlation between the equivalent width of the [O II] emission and radio size, but rather that at large ($\gtrsim$ 150 kpc) radio sizes the distribution of equivalent widths is fairly flat, and at small sizes there is often a factor of 2 to 3 excess emission relative to this level. Figure 6 shows that the size of the emission line region also changes as the radio source evolves. Excepting the unusual source 3C265, the emission line regions of radio sources with sizes $\gtrsim$ 200 kpc have total extents of up to about 50 kpc (25 kpc radius, if symmetrical). Smaller radio sources, however, have emission line regions ranging from this size up to about 100 kpc, a size comparable to the extent of the radio source. In other words, line emission at distances from the AGN of 30 to 50 kpc generally is only seen at the stage of radio source evolution when the hotspots are passing, or have just passed, through this region.

All of these properties can be well explained in terms of the shocks associated with the radio source (for details see Best et al. 2000b). As the shocks advance through the interstellar medium, the emission line clouds are accelerated by entrainment in the

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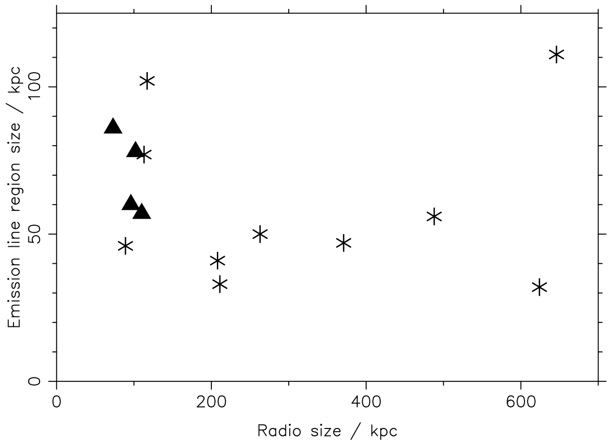

Fig. 6. The variation of the linear extent of the [O II] 3727 emission line region with the size of the radio source. Symbols as in Figure 2.

shocked intercloud gas, giving rise to the distorted kinematics and large FWHM observed in the small sources. The shocks compress the clouds, lowering their ionization state, and, if the shock is radiative, then an extra source of ionizing photons is also provided. This will boost the emission line luminosities of the small sources. The larger extent of the emission line regions in small sources arises since emission line clouds at radii $\gtrsim 30$ kpc only become luminous during the time when the radio shocks are passing through them and providing a local source of ionizing photons.

4. COMPARISON WITH LOW REDSHIFT OBJECTS

Baum et al. (1992) studied the ionization and kinematics of a sample of 40 radio galaxies with redshifts $z \lesssim 0.2$. They found that the FR II radio galaxies had kinematics which they generally classified as 'rotators' or 'violent non-rotators'. Best et al. (2000b) showed that the small radio sources in this sample are almost invariably associated with non-rotators whilst the larger sources were classified as rotators, exactly as is found for the high redshift sample. The probability of the radio sizes of the rotator and non-rotator classes being drawn from the same parent sample is less than 0.5%. Further, Baum, Heckman, & van Breugel (1990) present the line strengths of the [O I] 6300.3, [N II] 6548.1,6583.4, Hα and [S II] 6716.4,6730.8 emission lines of these galaxies. Although these are all relatively low ionization lines and therefore not the most sensitive to differences between shock and photoionization, the [O I] / Hα ratio should be higher for shock ionized gas than for photoionized gas. Best et al (2000b) showed that this emission line ratio is anticorrelated with radio size at the 96% confidence level.

Baum & McCarthy (2000) present kinematical properties of the emission line gas for 3CR radio galaxies ranging from $z = 0$ out to $z \sim 2$. They argue that there is little evidence for any correlation between radio source size and kinematical properties such as the emission line gas FWHM. However, their analysis considers galaxies at all redshifts simultaneously, and the strong correlation between FWHM and redshift swamps any FWHM versus radio size correlation. If the sources in their sample are split into two subsamples, at $z > 0.6$ and $z < 0.6$, then the $z > 0.6$ subsample shows a 99% significant inverse correlation between emission line FWHM and radio size, as found for our sample in § 3. Furthermore, the $z < 0.6$ subsample also shows a strong inverse correlation, of 97% significance, indicating that also at low redshift there is evidence for boosting of the emission line luminosity of small radio sources.

Thus, although all of the kinematic properties of the low redshift 3CR radio galaxies are less extreme than those at high redshift, they show exactly the same trends in their kinematic and ionization properties: larger radio sources have kinematics consistent with rotation and higher ionization states than small radio sources, whose ionization and kinematics show more evidence for the role of shocks. It is of note that the low and intermediate redshift sources for which individual studies have shown unambiguously that the kinematics and ionization are dominated by shocks are almost invariably cases in which the radio source is of comparable size to the extended emission line regions (e.g., Clark et al. 1997,1998), naturally agreeing with this picture.

5. PROPERTIES OF THE 6C RADIO GALAXIES

An important issue to understand is whether the more extreme kinematics seen in the high redshift 3CR sources compared to those nearby is a function of redshift or radio power, the two being tightly correlated in any flux limited sample. Decreasing the radio power has two effects: it will decrease the photoionizing output of the AGN, and it will decrease the kinetic energy supplied to the radio jets, which subsequently produce the shocks. The strong correlation between emission line luminosity and jet power (e.g., Rawlings & Saunders 1991) suggests that two properties will be decreased proportionally. Does this disturb the balance between the shock and photoionization?

Radio galaxies from the 6C catalogue are ideal for addressing these issues, since they are a factor

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of 6 fainter that the 3CR sources. This means that comparing 3CR and 6C galaxies at a given redshift (in this case $z \sim 1$) allows the radio power effects to be investigated independent of redshift, whilst comparing the 6C galaxies at $z \sim 1$ with lower redshift 3CR radio galaxies of the same radio power (those at $z \sim 0.3$) allows redshift effects to be studied. Eales (1985) defined a subsample of radio sources from the 6C catalogue for which spectroscopic redshifts are now available for 95% (Rawlings, Eales, & Lacy 2000). We (Inskip et al. 2002) have carried out equivalent observations to those of the 3CR galaxies of a matched sample of radio galaxies from this 6C sample with redshifts $0.85 < z < 1.3$. Full details of these observations, and their interpretation, are provided in the paper by Inskip et al., but some preliminary results are considered briefly here.

In Figure 1 the C III] 1909 / C II] 2326 versus [Ne V] 3426 / [Ne III] 3869 ratios are plotted for the 6C radio galaxies, for comparison with the 3CR galaxies and the theoretical lines. Although the spread of the points is somewhat larger than that of the 3CR galaxies, the data are still consistent with bimodal shock and photoionized populations. Figure 7 shows the carbon ratio plotted against radio size: clear evolution of the line ratio is again apparent, statistically significant at the 90% level (cf. 99% for the 3CR galaxies, and 99.5% for the combined population). We conclude that the ionization properties of the lower power radio sources match those of the 3CR sample.

Kinematically, the 6C galaxies also match those of the 3CR galaxies, as illustrated for example in Figure 8. The FWHM of the [O II] 3727 emission line evolves with radio size in exactly the same manner, and reaches values as high. This is in contrast to the 3CR radio sources at low redshift, of comparable radio power (e.g., Baum & McCarthy 2000), which typically show less extreme kinematics. This suggests that the difference between the low and high redshift 3CR sources is one of redshift as well as of radio power. This result is consistent with the finding of Tadhunter et al. (1998) that the ionization-sensitive [O II] 3727 / [O III] 5007 ratio does not decrease strongly with redshift as it should if the only difference between the low power, low redshift and the high power, high redshift objects was due to the change in the power of the AGN (and hence a change in the ionization parameter U of the photoionizing radiation).

The [O II] 3727 luminosity of the 6C radio galaxies is scaled down from that of the 3CR galaxies by a factor similar to the radio power. If the [O II] 3727 luminosities of the 3CR and 6C galaxies are all scaled to that of the same radio power according to the radio power versus line luminosity correlation of Rawlings & Saunders (1991) then both samples show equivalent radio size evolution, consistent with the boosting of the line luminosity of small sources due to the effects of shocks (Figure 9).

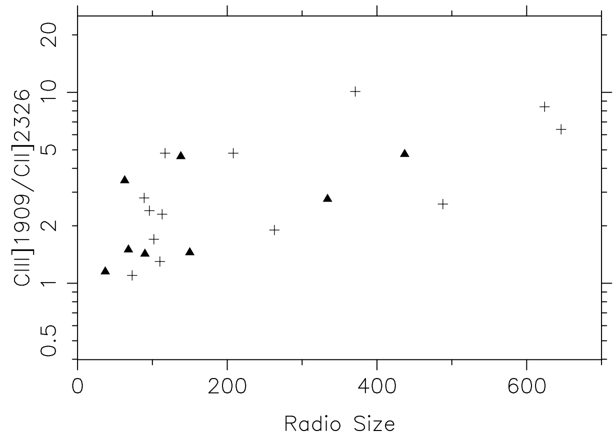

Fig. 7. The correlation between the C III] 2326 / C II] 1909 emission line ratio and the projected linear size of the radio source for both 3CR (asterisks) and 6C (filled triangles) galaxies. The 6C galaxies have similar carbon ratios to the 3CR sources and show the same trend with radio size.

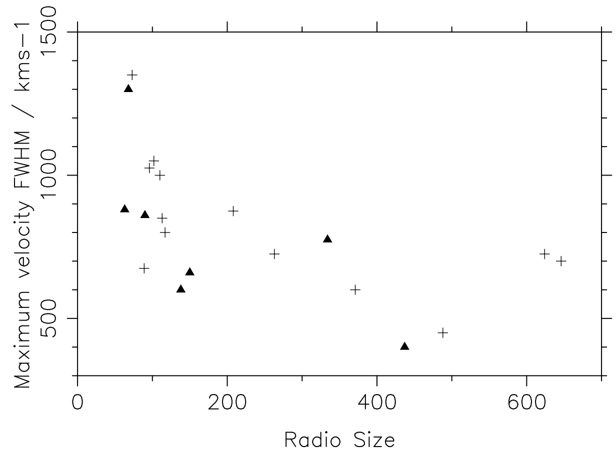

Fig. 8. The inverse correlation between the maximum FWHM of the [O II] 3727 emission line and the projected linear size of the radio source for 3CR (asterisks) and 6C (filled triangles) galaxies.

6. DISCUSSION

These results show that as the radio source shocks pass through the interstellar medium of the galaxy they have an enormous effect upon both the kinematic and ionization states of the emission line gas. This result holds at both high and low redshift,

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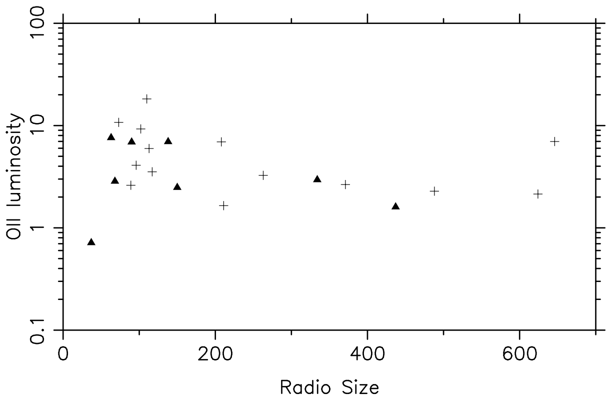

Fig. 9. The [O II] 3727 emission line luminosity (arbitrary units) plotted against radio size for the 3CR (asterisks) and 6C (filled triangles) galaxies, after correction of the luminosities using the line luminosity versus radio power correlation of Rawlings & Saunders (1991) to the mean radio power of the 3CR sources.

although the kinematics are more extreme at high redshift.

A number of authors have previously found little evidence for shocks when considering the ionization state of high redshift radio sources (e.g., Villar-Martín, Binette, & Fosbury 1999b), so it is interesting to consider why the observations presented here provide such definitive results by comparison. This issue was addressed by De Breuck et al. (2000), who considered various ultraviolet line ratios for a sample of high redshift radio galaxies and compared these with theoretical models. They showed that since, for example, the low ionization line C II] 2326 is weak in photoionization models but strong in shock ionized models, if even a small percentage of the total line emission of a galaxy is arising from shock ionized regions then the C II] 2326 line will be strongly boosted and its line ratios can be dramatically altered. Lines which are stronger in photoionization models, on the other hand, do not have their line ratios much altered in the presence of even up to 50% shock ionization. In the small radio sources discussed in the above sections which we describe as 'shock-ionized', the photoionizing AGN is, of course, still present, and will still be responsible for a large proportion of the ionization. Thus, many line ratios will be very little changed from photoionization predictions, including those considered by Villar-Martín et al. (C IV] 1549, C III] 1909, He II 1640 and Lyα); however, just a small fraction of shock ionization in these sources will have a large effect on the line ratios involving C II] 2326, such as that considered in this work. It is clear that some emission lines provide much better diagnostics of shocks than others.

Another issue worth considering is what other effects the radio source shocks may have. Particularly relevant here is the enhanced optical-UV emission of high redshift radio sources, which tends to be extended and aligned along the axis of the radio source in a similar manner to the emission line gas (the alignment effect, e.g., McCarthy et al. 1987). Best, Longair, & Röttgering (1996,1997) showed that this aligned continuum also evolves very strongly with the size of the radio source: smaller sources show many knots of emission tightly aligned along the radio jet, whilst larger sources are less luminous with more diffuse emission. Combined with the results for the emission line gas, this suggests that radio source shocks also play a key role in the continuum alignment effect. A detailed analysis of this is beyond the scope of the current paper, but broadly speaking this can be understood in terms of the two of the three most popular models for the alignment effect, as follows. Shock excitation of the emission-line clouds will give rise to an enhanced contribution of nebular continuum emission in small sources (e.g., see Dickson et al. 1995), exactly matching that of the increased emission line luminosity of those sources. Radio jet shocks may also induce the formation of massive knots of bright young stars (e.g., Rees 1989), which will disperse and fade over the lifetime of the source. These two mechanisms would each account for both the tight alignment of the optical-UV continuum emission along the radio jet and the observed variation in the luminosity of this emission with radio size.

7. CONCLUSIONS

Our conclusions can be summarised as follows:

1. Compared to their larger (older) counterparts, the emission line gas regions around small radio sources at high redshift have:
    - Line ratios consistent with shock ionization
    - Increased emission line FWHM
    - More distorted velocity profiles
    - Increased luminosity of their emission line
    - Larger physical extents

   From this, it can be concluded that as the radio source expands through the interstellar and intergalactic media, jet-cloud interactions play a very important role in determining both the ionization and kinematical properties of the emission line regions of small sources.

2. At low redshifts exactly the same trends are observed in the kinematic and ionization properties of radio galaxies, with the exception that the observed kinematics are, on average, much less extreme.

3. The properties of a matched sample of $z \sim 1$ 6C sources, a factor of 6 lower in radio power than the 3CR galaxies, are very similar apart from a global decrease in the emission line luminosity. Their kinematics are more extreme than matched radio power 3CR galaxies at lower redshifts, suggesting that the kinematical differences between the low and high redshift 3CR sources are due to redshift as well as radio power.

4. It is very important to carefully consider the emission lines to be studied when searching for signatures of shocks. Some lines, such as C II] 2326, provide excellent shock diagnostics.

5. The strong evolution of the optical-UV aligned continuum emission of these radio galaxies with the size (age) of the radio source is likely also to be due to radio jet shocks, arising through a combination of jet-induced star formation and enhanced shock-induced nebular continuum emission.

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