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The morphology of the emission line region of Compact Steep Spectrum radio sources

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ABSTRACT

We present the results of HST narrow band imaging of eleven Compact Steep Spectrum (CSS) radio sources. Five of them (3C 48, 3C 147, 3C303.1, 3C 277.1 and 4C 12.50) were observed as part of a dedicated “pointed” program of deep line imaging, at the redshifted wavelength of the \([\text{O III}] \lambda 5007\) emission line. For six additional sources (3C 49, 3C 93.1, 3C 138, 3C 268.3, 3C305.1 and 3C343.1) “snapshot” images ([O III] \(\lambda 5007\) or [O II] \(\lambda 3727\)) were taken from the HST archive.

In all but one of the targets (3C 49) line emission has been detected and only in the case of 3C 138 is it unresolved at the HST resolution. Three distinct components are found in the CSS emission line morphologies: 1) compact nuclear emission regions

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whose size is less than a few kpc: 2) bright emission spatially related to the radio structure; and 3) faint emission which extends well beyond the radio source.

A large fraction of the line emission (between 30% and 90%) originates within less than $\sim 3$ kpc from the nucleus as in the case of Seyfert and extended radio galaxies.

In four out of five of the sources for which deep observations are available the line emission extends well beyond the size of the radio source but along the radio axis. Only in the case of the largest radio source (3C 277.3) no emission beyond the radio lobes is detected. Structures of similar surface brightness would have not been seen in the snapshot images. These emission line structures extend to scales of 10 to 30 kpc and cover a projected angle, when seen from the nucleus, of $\sim 30^\circ - 110^\circ$, and indicate that the nuclear illumination is anisotropic. Photon counting arguments also support this interpretation. In agreement with the AGN unified scheme, only the CSS with Broad Line Regions show a strong unresolved continuum source in the HST images.

In six objects the radio emission extends over more than 1″ and the HST resolution is such that a detailed comparison can be made between radio and optical morphologies. In these cases the line emission has an elongated structure, linking the nucleus to the radio-lobes, possibly tracing the path of the invisible radio jets.

Nevertheless the emission line morphologies do not show the bow shocks at the extremities of the radio lobes one would expect if they are sources whose expansion is frustrated by a dense external medium. Our data favour the alternative model in which CSSs are the young phase of the large size radio sources.

When “pointed” pure continuum images are available, there appears to be no alignment between radio and continuum emission which contradicts previous suggestions based on broad-band HST imaging. We suggest that these broad band images are in most cases heavily contaminated by line emission, producing a spurious apparent alignment.

Subject headings: Galaxies — active

1. Introduction

In the unified scheme for active galactic nuclei (AGN) broad and narrow line objects are intrinsically the same, but are viewed at different orientations. The orientation dependence arises either as a result of preferential obscuration created by a surrounding torus of dust material, as in Seyfert nuclei, in powerful radio galaxies, as a result of relativistic effects (Antonucci 1993, Urry & Padovani 1995). It follows that a fundamental question for the unified scheme is to establish the degree of anisotropy of the radiation field in radio loud AGN. The other important question is the balance between the relativistic beaming and radiation cone illumination as a function of radio-power and source luminosity. In reality the situation can be made more complex
by secondary effects, such as intrinsic angle dependence of the radiation pattern produced by an accretion disk. It is not as yet clear if radiation cones exist in the majority of more luminous sources because these obscuring structures might be evaporated by the radiation field (i.e. the absence of quasars type 2).

The study of the gaseous environment around Active Galactic Nuclei provides a potent tool for studying both their radiation field and the mechanical energy carried by the associated radio ejecta. In most of the radio galaxies studied to date the emission line gas is co-spatial with the radio emission and therefore contributions to their ionization made by the turbulent shocks created by the ejecta cannot be distinguished from photoionization by the nuclear radiation field. However there is a group of radio sources, known as Compact Steep Spectrum (CSS) sources, where the radio emission is confined to scales smaller than typical galactic sizes. Compact steep spectrum (CSS) sources are high luminosity extragalactic radio sources with steep radio spectra ($\alpha \geq 0.5$, with $S \sim \nu^{-\alpha}$) and small radio angular size ($\leq 2''$, $\leq 30$ kpc) (Fanti et al., 1985, Spencer et al. 1989). The CSSs are believed to represent either a young phase of powerful extragalactic radio sources (Fanti et al. 1995, Readhead 1995 and references therein) or radio sources trapped by unusual conditions of their ISM (e.g. van Breugel, 1984) which prevents them from growing to normal dimensions. Hes, Barthel & Fosbury (1996), Hirst et al. (1996), Morganti et al. (1997) have found that their spectroscopic and polarimetric characteristics are similar to those of the extended sources of similar power and redshift. Any emission line gas extending beyond the radio structure would not be affected by interactions with the radio ejecta. In this sense they would be the analog of the Extended Narrow Line Region (ENLR ) of Seyfert galaxies (Unger et al. 1987). The ENLR of CSS sources might, therefore, provide a direct probe of the anisotropy of the radiation field in radio galaxies and QSOs while in the region co-spatial with the radio ejecta the effects of jet cloud interaction on the evolution of the radio sources can be investigated.

Fanti et al. (1995) have recently investigated if the conditions of the external medium (warm and hot gas) around CSS sources can keep them small by confinement. They conclude that this scenario is unlikely, although not definitely ruled out, and they support the idea of CSS as young phase of large size radio sources. Moreover, by studying a small sample of CSS sources, Gelderman and Whittle (1994, hereafter GW94) have shown that the profiles of the NLR are broader and complex and suggest that this is the result of the jet interaction with the external medium.

The limitation of these optical studies is that they are based on ground-based data where the resolution of the optical observations is not adequate for these objects. In this paper we present the results of HST observations of 11 CSS sources. The high resolution of the HST allows us to resolve the morphology of the ionized gas in the region co-spatial with the radio enabling us to investigate the role of interactions and their influences on the evolution of these sources. The plan of the paper is as follows: in § 2 we describe the properties of the sample observed. In § 3 the observations. In § 4 and 5 we present our results comparing the optical HST images with radio images of similarly high resolution. The properties of the line emitting regions of CSS are
discussed in § 6 while the nature and evolution of CSS sources in the light of these results is discussed in § 7. In § 8 and 9 we analyze the importance of orientation and the alignment effect in CSS respectively. Summary and conclusions are given in § 10.

Throughout this paper we adopt $H_o = 50 \text{ km s}^{-1} \text{Mpc}^{-1}$ and $q_o = 0.5$.

2. The Sample and its radio properties

Our sample comprises 11 objects covering the redshift range 0.12 to 1.12: 5 of which have been observed with “pointed” observations (Table 1) while the remaining 6 are “snapshot” images (Table 2) taken from the HST archive. Of the 11 objects, 4 have permitted broad lines in their spectra and are generally classified as Quasars ($Q$) while the remaining 7 only have only narrow lines and are classified as radio galaxies ($G$)

The radio sources of the sample are all very powerful, with radio luminosities $\geq 10^{26}$ W/Hz at 2.7 GHz. Their radio data are summarized in Table 3. In seven sources, out of eleven, the radio core has been detected. The core luminosities are similar to those of radio galaxies and radio quasars of larger linear size. The parameter $P_{cn}$ (which represents the ratio of core to extended flux, normalized to the median value of the object class) is an orientation indicator (Capetti et al., 1995a). The range of $P_{cn}$ values of our sources indicates that the sample is not preferentially biased in orientation compared to the population of CSS as a whole.

The radio morphology is double in 8 out of 11 objects. We suspect that also 4C 12.50 might be a double source in which one of the lobes has been missed (Stanghellini et al. 1997). 3C 48 and 3C 93.1 have rather peculiar radio structures. In general there are significant asymmetries between the two lobes, both in flux and arm ratio (ratio of distances from the lobe edges to the core) and often the lobe closer to the core is also the brightest one (Fanti et al., 1990, Sanghera et al., 1995).

In Table 3 we have also included in column 10 and 11 the $[\text{O III}] \lambda 5007$ (or $[\text{O II}] \lambda 3727$) line fluxes found in the literature.

3. The HST Observations

3.1. Pointed observations

Narrow band images for 3C 48, 3C147, 3C 277.1, 3C303.1, and 4C12.50, were obtained in a dedicated program of line imaging of CSS radio galaxies. The observations were taken using the Linear Ramp Filters (LRF) of the Wide Field and Planetary Camera 2 (WFPC2) on board the Hubble Space Telescope. With the LRF each CCD pixel is mapped to a unique central wavelength with a FWHM bandwidth of $\sim 1.3\%$ of the central wavelength, which allows the production of narrow band images at any given wavelength over a field of view of $\sim 13''$. The redshifted
wavelength of the [O III]λ5007 emission line was selected for each of the targets (see Table 1 for the log of the observations).

A continuum image was obtained for each target using the LRF centered in rest frame wavelength range 5400 - 5500 Å. The LRF were preferred to more efficient, broader filters since they allow us to isolate a region of continuum emission completely free of line emission. Therefore, although they produce images of relatively lower signal to noise (with a typical surface brightness limit of $1 - 3 \cdot 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$), the genuine continuum structure of the targets can be effectively explored and compared to the line and radio emission structure. At these wavelengths the Point Spread Function of HST has a FWHM of $\sim 0\farcs06$.

In all cases the selected wavelength corresponds to a location in one of the three Wide Field (WF) CCD chip, where the pixel size is $0\farcs1$, except for 3C277.1 whose on-band image falls into the Planetary Camera (PC) which has a pixel size of $0\farcs0455$.

Three on-band and one off-band images with an exposure time ranging between 1100 and 1330 s each were taken. The data were processed through the PODPS (Post Observation Data Processing System) pipeline for bias removal and flat fielding (Burrows et al. 1995). Individual exposures in each filter were combined to remove cosmic rays events. In the off-band images cosmic rays have been individually identified and removed by taking averaged values from neighbouring pixels.

The line and continuum images were aligned by registering point sources present in both fields of view, except for 3C 48 where the central point source was used.

The off-band images were scaled to reproduce the continuum contamination in the on-band images by taking into account the different exposure time and filter efficiency as derived from the internal WFPC2 calibration which is accurate to within 5 %. The 3σ sensitivity of the resulting LRF images is typically $1.5 \cdot 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ for point sources.

### 3.2. Snapshot observations

HST narrow band images for an additional 6 CSS are available in the HST archive, obtained as part of a “snapshot” (two exposures of 300 s each) program of observations of the 3C sample of radiogalaxies (see table 2 for the observations log). Furthermore, snapshot observations duplicate our much longer pointed exposures of 3C277.1 and 3C303.1; we can use these to quantify the relative depth of the two surveys.

The LRF filter were used and centered on the [O III]λ5007 emission line for target with $z < 0.5$, and on the [O II]λ3727 line for $z > 0.5$. 3C 138 was observed through the F656N narrow filter which covers the redshifted [O III] emission. As for the pointed observations the selected wavelength always correspond to locations in the WF chips (with the exception of 3C 138 which was imaged by the PC).
Snapshot broad band images are also available for all targets (one or two exposures of 140 or 300 s each). The F702W wide filter, which covers the spectral range 6000 - 8200 Å was used. In all cases the emission line imaged with the LRF is included in the passband of the F702W filter. The targets were all located in the PC.

The snapshot data were reduced using the same procedure as for the pointed observations. The $3\sigma$ sensitivity of the snapshot LRF images is typically $8 \cdot 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ for a point source. In general the snapshot data are read-noise limited and there is therefore a very large gain in signal to noise in the pointed observations, which are photon noise limited.

4. Results

In all but one of the targets (3C 49) line emission has been detected and only in the case of 3C 138 it is unresolved at the HST resolution. A large variety of emission line components are found, compact nuclear emission regions whose size is less than a few kpc, bright emission spatially related to the radio structure and faint emission which extends beyond the radio source.

In Figures 1 through 7 we show the HST and contour radio images of each source for which we detected extended line emission. For each target observed with the pointed observations the top right panel presents the on-band image and the top left panel shows the off-band image, scaled to reproduce the continuum contamination in the on-band image which is, in all cases, negligible. In order to emphasize low surface brightness line features a higher contrast line image is presented in the bottom left panel. A radio contour map is shown in the bottom right panel. Given the typical 1" uncertainty in the relative astrometry of the HST and radio images no attempt has been made to directly overlay radio and optical images, although in several cases the alignment is straightforward because there is both a radio core and an optical nucleus.

For the snapshot observations the left and central panels show the F702W and LRF images respectively. Since the broad band F702W filter includes the line emission observed with the LRF, and other emission lines, only upper limits to the continuum contamination can obtained. This prevents us from obtaining accurate photometry for these objects. However, in all cases, the on-band image is dominated by line emission. Conversely, significant line contamination occurs in the broad band filter images which explains the similarity observed in many cases between the narrow and broad band image.

Table 4 gives the total and core [O III] $\lambda 5007$ fluxes (estimated within a circular aperture 0.1 - 0.3 in diameter) and the nuclear continuum flux for the objects with pointed observations. There is a good agreement between these values and those found in the literature.

5. Notes on the individual sources
5.1. Pointed Observations

5.1.1. 3C 48

Both the on and off-band images of 3C 48 are dominated by a bright central nuclear source. Several compact knots form chains of line emission extending to a distance of 6″ North of the nucleus. These features correspond to the structures originally seen by Stockton & MacKenty (1987). The presence of the central saturated point source does not allow us to investigate the structure of the central 0″5. However, the comparison with the continuum image indicates that significant line emission is confined to this region. In fact, the extended emission only accounts for ~ 10 - 15% of the [O III] flux measured from previous ground-based spectra (GW94). The GW94 data also show that [O III] line profile is very broad and flat-topped. Our unpublished data at higher spectral resolution show that this a consequence of the presence of two velocity systems indicating some kind of dynamical interaction, presumably with the radio jet.

The best radio images are the VLBI data of Wilkinson et al. (1991). Two knots of high brightness dominate the radio emission in 3C 48. They are separated by ~ 0″05 with a North-South orientation. The southern one has a flat spectrum and therefore is identified with the radio core. A highly asymmetrical lower brightness emission region extends toward the North-East for a total length of ~ 0″8 and is bounded by a sharp edge. The small scale radio structure shows a rapid expansion of the radio source at ~ 0″1 from the core. The absence of diffuse, more extended emission in lower resolution images (van Breugel et al., 1992) supports the VLBI result that the the radio emission is confined to ~ 1″.

5.1.2. 3C 147

The emission line morphology of 3C 147 is also dominated by an unresolved central source, embedded in a more diffuse region, elongated along PA +30° and which extends over ~ 1″2, approximately symmetric with respect to the center of the continuum emission. Along the same axis, ~ 1″8 South from the nucleus there is a faint arc-like structure. Note that the two compact knots at the eastern edge of this arc are continuum features (see Fig. 8). The emission line arc extends over ~ 1″3 and spans PA ~ 185° to PA ~ 230°. Another galaxy, possibly a companion, is located 3″9 away at PA 190°.

The double radio structure (van Breugel et al., 1984) is oriented along PA ~ +30° and extends over ~ 1″ and it is therefore well aligned and essentially cospatial with the line emission. The southern component envelopes a very bright jet. The radio core is well separated from the surrounding bright 3C 147 steep spectrum emission at high resolution only (Alef et al., 1991).
5.1.3. 3C 277.1

The line emission of 3C 277.1 extends over 1"5 in a NW - SE direction. The overall structure forms a double shell-like morphology, with the NW lobe brighter and with a better defined morphology. The central unresolved source contains \( \sim 30\% \) of the total line emission.

The radio source has a triple structure of which the central component is the radio core, characterized by a flat spectrum (Sanghera et al. 1995, Akujor et al. 1995). The two lobes, separated by 1"1 and 0"4 respectively from the core, are oriented along PA -50°. Registering the radio core on the peak of the line emission, we find that the northern lobe extends beyond the emission line gas, while the southern one is still embedded within it.

5.1.4. 3C 303.1

The \([\text{O III}]\) \(\lambda5007\) emission of 3C 303.1 has a striking S-shaped morphology, reminiscent of the NLR structure of the Seyfert galaxy Mrk 3 (Capetti et al. 1995b). Its brightest inner structure is oriented along PA \(\sim -40°\) and it then swings in a NS direction, extending over \(\sim 3″\). The central and brightest blob is coincident with the continuum peak but is clearly dominated by line emission. An arc-like structure, perpendicular to the overall orientation of the line emission is located toward the South at a distance of \(\sim 1″7\) from the nucleus. The galaxy starlight is highly elongated along PA \(\sim 0°\).

The radio emission is an asymmetric double (Fanti et al., 1985), with the SE lobe brighter than the NW lobe. It is oriented along PA -47° and extends over 1″8. No radio core has been detected yet, so the registration of the radio and optical images is somewhat uncertain. However, both radio lobes are likely to be located outside the region \([\text{O III}]\) \(\lambda5007\) emission, due to the change in the optical orientation for radii larger than 0″5. The arc-like line emission structure to the south has no corresponding radio counterpart.

5.1.5. 4C 12.50 (1345+125)

The optical identification of 4C 12.50 is controversial. Ground based imaging by Gilmore & Shaw (1986) revealed a complex optical morphology, with two nuclei separated by \(\sim 1″8\) embedded in a distorted common envelope. They associated the radio source with the eastern optical component since this is closer (0″4) to the radio position than the western nucleus (which is offset by 1″0). However, new astrometry by Stanghellini et al. (1993) leads to the opposite result. We measure the position of the optical nuclei in our HST images. They are located at RA = 13\(^{h}\) 47\(^{m}\) 33\(^{s}\).49, DEC = 12° 17′ 23″.40 and RA = 13\(^{h}\) 47\(^{m}\) 33\(^{s}\).36, DEC = 12° 17′ 23″.85 (J2000) and the offsets from the radio source (RA = 13\(^{h}\) 47\(^{m}\) 33\(^{s}\).31, DEC = 12° 17′ 23″.99) are 2″4 and 0″6 for the East and West components respectively. Even considering the accuracy of the
HST absolute astrometry, \( \sim 1'' \), it appears that the most likely identification of 4C 12.50 is the Western nucleus and it will adopted in this paper.

The central component of the line emission is very compact and shows a faint elongation towards the West. At 1'' North there is an arc-like structure, which extends \( \sim 1'' \) perpendicular to the direction to the nucleus. Fainter diffuse emission is found 2'' North of the nucleus.

The radio emission (Stanghellini et al., 1997) is confined within \( \sim 0.1'' \) (300 pc). It shows a distorted, triple morphology oriented approximately along PA \(-20^\circ\). The compactness of 4C12.50 is confirmed by the VLA observations of Crawford et al. (1996) in which it appears unresolved.

5.2. Snap-shot Observations

5.2.1. 3C 49

3C 49 is the weakest source in our sample and there is only marginal evidence for line emission in the narrow band image which is not presented. The broad band image (de Vries et al. 1997) shows a central compact component and a faint elongation, less than 1'' in size, along PA \(-55^\circ\).

The radio source associated with 3C 49 has a double asymmetric structure elongated in the EW direction (Fanti et al., 1989), with a weak core closer to the brighter western lobe. The overall size is \( \sim 1'' \).

5.2.2. 3C 93.1

The central optical source is marginally extended along PA \(+60^\circ\) and is dominated by line emission. A faint emission-line feature extends \( \sim 1'' \) from the nucleus along \( \sim 45^\circ \). The radio structure is both complex and compact (\( \sim 0.6'' \)), about a factor of 2 smaller than the emission-line region (Dallacasa et al., 1995).

5.2.3. 3C 138

3C 138 appears unresolved at the resolution and sensitivity of the snapshot images which are presented. However, the central continuum source accounts for only 15 % of the on-band emission, indicating that line emission is associated with its nuclear regions and it originates in a very compact region, \( \leq 0.1'' \) (1.5 kpc). The radio source has a triple structure, with a bright radio core and a bright jet embedded in the NE lobe. Around the radio core position Cotton et al. (1997) found a large Faraday rotation measure which is likely to occur in the compact line emitting region. In contrast, in the northern jet/lobe, the rotation measure is virtually zero, consistent with the lack of line emission indicating the presence of little warm gas.
5.2.4. 3C 268.3

The line emission has a jet-like morphology which extends 0″7 NE and 2″0 toward the SW from the center of the host galaxy. In the brightest regions it is oriented along PA -45° while it bends toward smaller position angles in the fainter extensions on both sides. The central component is also dominated by line emission. Another galaxy, possibly a companion, is seen 2″ SW of 3C 268.3.

The radio emission has an asymmetric double lobed morphology (Fanti et al., 1985), extended ∼ 1″4 along PA -20°, clearly misaligned with respect to the line emitting gas. A weak core is detected, closer to the southern component (Ludke et al. 1998). Registering the radio core on top of the peak of line emission, shows that the northern lobe is at the edge of the line emission, while the southern, due to the difference in optical and radio PA, is outside the line emission region.

5.2.5. 3C 305.1

The on-band image shows an elongated structure, extending over ∼ 1″5 along PA ∼ +30°, which is also seen in the F702W image. The comparison between the narrow and broad band images indicates that this is dominated by line emission.

The radio emission forms a double lobed structure with a separation between the two components of ∼ 2″. The radio axis is at PA -10°. The radio core has not been detected, so that a good registration of the optical and radio image is not possible. However, almost certainly both radio lobes are outside the line emitting region.

5.2.6. 3C 343.1

The broad-band image reveals a linear feature, 0″5 in size, oriented approximately along the EW axis, which is superposed on more diffuse emission. The similarity to the structure seen in the narrow band image indicates that they are dominated by emission lines.

The radio source has a double structure, with overall size ∼ 0.38 ″, and is oriented EW. The two lobes are different in flux and shape, the western one being more luminous and broader. No radio core has been detected yet, so that the registration of the optical and radio image is somewhat uncertain. However it is likely, that both radio lobes are still embedded in the NLR.

6. The properties of the emission line regions in CSS

Ground-based spectroscopic studies of CSS have been carried out by GW94, Baker et al. (1996), Hirst et al. (1996) and Morganti et al. (1997). CSS radio sources have optical spectra
which, to first order, are typical of powerful radio galaxies. In all cases, strong emission lines and high (or medium) ionization spectra have been found. It is therefore not surprising that all our objects are detected in our new [O III] $\lambda 5007$ images, while only one is undetected in the [O II] $\lambda 3727$ images.

However, one of the new results of this study is that EELR, extending beyond the radio emission, are commonly found in CSSs. Clearly, unlike the conventional radio galaxies, this extended gas cannot be excited by interaction with the radio outflow and is presumably therefore photoionized by the nuclear radiation field. Furthermore, for the well resolved objects we see a correlation between radio and line emission structures. In the following sections we will elaborate on these results.

6.1. The inner emission line regions

In all on-band images, with the possible exception of 3C 49 and 3C 305.1, a central compact (smaller than $0''3$) component is seen. The comparison with the continuum or the broad band images clearly indicates that these central sources are dominated by line emission. A large fraction of the line emission (between 30% and 90%) originates within $0''1$ - $0''3$ of the nucleus, corresponding to a linear scale of less than $\sim 3$ kpc. The narrow filter passband, which is less than 90 $\AA$ wide, includes only the forbidden [O III]$\lambda \lambda 4959,5007$ (or [O II] $\lambda 3727$) lines. Any contribution from permitted broad lines is excluded. We are observing compact Emission Line Regions, commonly observed in extended radio-galaxies, and whose size is comparable to the typical extension of the NLR of Seyfert galaxies.

6.2. The extended line emitting regions

In four of the pointed sources, 3C 48, 3C 147, 3C 303.1 and 4C12.50, the line emission extends well beyond the radio structure. Not surprisingly these are sources for which pointed observations are available. We also note that the only source for which we have pointed observations which does not show line emission extending beyond the radio lobes is 3C 277.1 which is the largest amongst these radio sources. We conclude that line emission, on a scale significantly larger than the radio emission, is commonly detected when the images are sufficiently deep.

The structure of this extended emission is intriguing. In three cases (3C 147, 3C 303.1 and 4C12.50) it takes the form of an arc-like feature perpendicular to the radio axis, but displaced far beyond the lobe edge. In 3C 48 it is quite different being concentrated in arm-like structures which are nonetheless located essentially along the radio axis. The gas responsible for this extended emission is localized in well defined structures. Again, this is very similar to what is observed in the ENLR of Seyfert galaxies (e.g. NGC 5252, Tadhunter & Tsvetanov 1989, and Mrk 573, Capetti et al. 1996) which are composed of arcs and filaments of gas. Both in CSS and Seyferts,
these structures are found approximately in the direction of the radio axis but they are elongated in a direction perpendicular to it.

The origin of the illuminated shell structures is unclear. They might have formed in a previous phase of nuclear activity as a result of compression of the ISM by radio ejecta. The lack of associated radio emission requires a long time scale between the different nuclear phases. Alternatively, these structures might be intrinsic to the gas distribution of the galaxy. For example, gaseous shells might have been formed due to a merger and in this case we only see those parts which are illuminated by the nuclear radiation field.

The projected angle covered by these structures, as seen from the nucleus, varies from $\sim 30^\circ$ in 3C 303.1, to $\sim 45^\circ$ in 4C 12.50 and 3C147, to $110^\circ$ in 3C 48. Since the line emission is tracing the intersection between the gas and the geometrical pattern of the nuclear radiation, either the radiation field is highly anisotropic or the gas is located only along the radio axis. We will discuss the issue of anisotropy further in Section 7 from the perspective of “photon counting”.

### 6.3. The association between radio and optical emission

In six sources (3C 147, 3C 268.3, 3C 277.1, 3C 303.1, 3C 305.1 and 3C 343.1) the size of the radio emission is such that we can study the relationship between radio and optical structures.

In 3C 303.1 and 3C 268.3 the radio emission has a double lobed morphology and the line emission originate in two symmetrical jet-like structures which connect the central source with the radio lobes. The images of 3C 305.1 are clearly of lower quality, but this source appears to share a similar elongated morphology. These linear structures of the line emission follow the radio axis, suggesting that they are tracing the path of the undetected radio jets which are feeding the lobes. It is likely that the compression caused by interaction between the jets and the external medium causes the emission to be highly enhanced along their path (Taylor et al. 1992). The very broad (FWHM up to 2000 km/s) and flat topped line profiles commonly observed in CSS (e.g. GW94) are also an indication of jet-induced gas acceleration. Interestingly, the line emission is always slightly mis-aligned with respect to the radio axis and its structure is not exactly straight but clearly curved. Although it is possible that the invisible jets are indeed bent, this is not usually the case in the more extended, double lobed, radio source (e.g. Cygnus A) in which the highly supersonic jets are quite linear. The results obtained for these sources are very reminiscent of what is observed in Seyfert galaxies in which there is a close association between radio and line emission and similarly a slight misalignment between the radio jets and optical emission is observed (Capetti et al. 1995b). Capetti et al. interpreted this as due to the expansion of the radio source in a stratified gas distribution and it is likely that this idea is also applicable to the CSSs.

The situation is more complex for 3C277.1: the SE radio lobe is located at the edge of the line structure. Conversely the NW lobe is well outside the shell-like line emitting region. In 3C343.1
and 3C 147 the smaller size of the radio structure does not allow us to perform a detailed analysis, but clearly the radio and the line emission are well aligned and of very similar angular size.

Overall, we do not find any clear connection between radio structure asymmetry and line emission asymmetry. For instance, in 3C277.1 the lobe closest to the core is associated with the brightest region of line emission, while the converse is true for 3C268.3.

7. The ionization mechanism

Optical spectra of CSS sources are available only for a handful of 3CR sources from GW94 and Hirst, Jackson & Rawlings (1996) and for those amongst the complete 2-Jy sample studied by Morganti et al. (1997). A comparison of the emission line luminosities of CSS sources with those of extended radio sources has been recently carried out by Hes, Barthel & Fosbury (1996) and by Morganti et al. (1997) for the 2Jy sample.

The log L_{[OIII]} vs log P_{radio} plot, including [O III] luminosities from the HST data, is shown in Fig. 8 in which CSS sources are marked with filled symbols. Although, admittedly, the spread in the correlation is large, for a given radio power, the CSS have [OIII] luminosities comparable to those of the extended sources. Similarly CSS quasars and CSS radiogalaxies are indistinguishable on this plot (cf. Hes et al. 1996, and Morganti et al. 1997).

This overall similarity of the CSS and extended sources indicates that they have, at least to first order, their emission-line regions have similar physical conditions and ionization mechanisms.

Typical line ratios of the narrow line component in CSS (GW94) are:

\[ \frac{H_\beta}{[O \text{ III}] \lambda 5007} = 0.18 \pm 0.02 \]

\[ \frac{[O \text{ II}] \lambda 3727}{[O \text{ III}] \lambda 5007} \approx 0.3 \pm 0.05 \]

\[ \frac{(H_\alpha + [N II])}{H_\beta} \approx 7.5 \pm 1.5 \]

These line ratios are consistent with photoionization by a power-law continuum from the nucleus (Robinson et al. 1987). Nevertheless, it is important to check that the nucleus is actually sufficiently luminous to provide the required ionizing flux. We do this by comparing the ionizing photon luminosity determined from the emission line fluxes using photon-counting arguments with that inferred by extrapolating the observed optical continuum of the nucleus. We first calculate the rest-frame optical luminosity, \( L_{\nu, \text{opt}} \), for each source using the fluxes listed in Table 4. Representing the optical–X-ray continuum by a power-law of spectral index, \( \alpha_{ox} \), the ionizing photon luminosity is given by

\[ Q_{ext} = \frac{L_{\nu, \text{opt}} \left( \frac{\nu}{\nu_H} \right)^{\alpha_{ox}}}{h |\alpha_{ox}|} \]  

(1)
where \( \nu_F \) and \( \nu_H \) are, respectively, the frequencies corresponding to the filter central wavelength and the Lyman limit. We adopt the average value of the optical–X-ray spectral index, \( \alpha_{ox} \approx -1.3 \) found by Brinkmann et al. (1997) for radio loud AGN. The ionizing photon luminosities determined in this way are listed in Table 5.

The ionizing photon luminosity necessary to sustain the line emission is easily calculated from the H\( \beta \) luminosity. In order to estimate the latter we multiply the measured [OIII] \( \lambda 5007+4959 \) fluxes (Table 4) by the factor \( 3/4 \times \) the typical \( H\beta/[\text{O III}] \lambda 5007 \) ratio for CSS quoted above, and use the result to calculate the rest frame luminosity. The minimum ionizing photon luminosity required to produce the \( H\beta \) emission corresponds to the limiting case in which all ionizing photons are absorbed, that is, the covering factor of the emission line region is unity. This is given by

\[
Q_{\text{min}} = \frac{L_{H\beta}}{p_{H\beta} \nu_{H\beta}}
\]

where \( p_{H\beta} \approx 0.1 \) is the probability that any recombination will result in the emission of an H\( \beta \) photon.

We have calculated minimum ionizing photon luminosities for both the NLR and the EELR; their ratios to \( Q_{\text{ext}} \) are listed in Table 5. If the nuclear ionizing continuum is isotropic these ratios are equivalent to the covering factors of the respective emission line regions.

There is a clear difference between the two quasars for which we have emission line fluxes, and the two radio galaxies. In the quasars, < 20% of the available ionizing photons need to be absorbed in the NLR to produce the line emission. Since this fraction seems reasonable for the NLR covering factor, we conclude that the photon budget is consistent with pure photoionization by the nuclear continuum source. The nuclear continuum sources of the quasars are also powerful enough to photoionize their extended emission line regions. The implied covering factors are relatively high (\( \approx 0.3 \) and \( \approx 0.4 \), respectively) but inspection of the images (Figs 2 and 3) shows extensive [O III] \( \lambda 5007 \) emission widely distributed around the nucleus in both cases. Furthermore, our power-law extrapolation may underestimate the true ionizing luminosity if the “big blue bump”, which is ubiquitous in quasars, contributes significantly to the EUV continuum.

For the radio galaxies, on the other hand, the inferred ionizing luminosity is barely sufficient to power the NLR emission, with covering factors \( \approx 0.5 \) and \( \approx 1 \), respectively, being required. The ionizing photon budget for the ELR in 3C 303.1 appears to be even more difficult to reconcile with nuclear photoionization, since \( Q_{\text{min}} \) exceeds \( Q_{\text{ext}} \) by a factor \( \approx 5 \). This is entirely consistent with what we expect on the basis of unified schemes for radio-loud AGN. These schemes hold that the central continuum source and broad-line region are surrounded by a dusty molecular torus, with radio galaxies and quasars being identified as “edge-on” and “pole-on” sources, respectively.

If this is correct, the optical continuum observed in the radio galaxies is unlikely to come directly from the active nucleus and therefore the calculated values of \( Q_{\text{ext}} \) will not reflect the true nuclear ionizing photon luminosity. For this reason, we cannot exclude AGN photoionization of either the
NLR or ELR in the two radio galaxies, even though the calculated covering factors are implausibly high. These results can be explained if the nuclear radiation field is anisotropic.

Another possibility is that shock ionization is important. Recently a jet-driven auto-ionizing shock model for the line emission has been presented by Bicknell et al. (1997). In order for emission lines to be observed requires both that the velocities are \( \leq 10^3 \text{ km s}^{-1} \) and that the external densities (\( > 10^2 \text{ cm}^{-3} \)) are high, so that the cooling time of the shocked gas is smaller than the dynamical time of the radio source. Of course this mechanism cannot apply in those cases in which the emission lines originate beyond the radio emission.

As described in Section 6, in all sources in which the size the radio emission extends over more than 1′′, and which are therefore sufficiently extended to be fully resolved by our HST images, the bow shock structures which in this model are expected to enshroud the advancing radio-lobes are not observed. This indicates that the leading shocks are already in a non radiative phase when the radio source size exceeds a typical scale of \( \sim 5 - 10 \text{ kpc} \) and do not produce significant line emission when compared to the total source line luminosity.

In contrast, the innermost regions of line emission in these CSS can be powered by fast shocks which are laterally expanding in the regions where the ISM is denser and with a shorter cooling time. This argument also applies to the unresolved CSS of our sample. In general to establish which mechanism dominates, requires a combination of UV line diagnostic ratios (Allen et al. 1998) and shock velocities determined from kinematic studies. In this context spectroscopy with the HST would be critical in separating the NLR from the ENLR in CSSs.

8. The nature and evolution of CSS

As we described in the Introduction CSSs may be either young or frustrated radio sources. While it is clear from our present data that the larger CSS are currently not trapped by ambient gas the question remains if their earlier evolution was significantly impeded by the environment or if the smaller CSS in our sample are still frustrated. Here we use our new data and data available in the literature to investigate this issue.

De Young (1993) and Fanti et al. (1995) have shown that, in order to confine average power CSSs for periods in excess to \( 10^7 \) years, an ambient gas of number density \( > 1 - 10 \text{ cm}^{-3} \) (with corresponding core radii from 5 to 1 Kpc) is required. The mass of gas implied by the “frustration scenario” is always rather large, \( \geq 10^9 M_\odot \). If this gas exists, the problem is to find out the kind of medium (hot, tepid, cold). While it seems (O’Dea et al., 1996) that the (limited existing data exclude a hot (\( \geq 10^7 \)) medium, which would produce copious X-rays it is still possible that a cooler confining medium exists.

We can use the line luminosities to investigate if the density of line emitting gas is adequate to trap the radio ejecta. From our images we can estimate the size of the emission line regions as
well as the associated [OIII] luminosities. When no HST photometry is available we used data from GW94. The [O III] luminosities are converted to narrow $H\beta$ luminosities using an average ratio of $0.18 \pm 0.02$. We preferred this average value to that measured for individual objects in GW94 since they include also an unknown contribution from the broad $H\beta$ line. Since the HST and GW94 luminosities are in reasonable good agreement, this implies that they refer to the same emitting volume. When the [O III] $\lambda5007$ line is not available, we use the [O II] $\lambda3727$ luminosity and convert it to $H\beta$ by a factor $0.6 \pm 0.1$.

Assuming a case B (Osterbrock 1989) model the $H\beta$ luminosity is given by:

$$L(H\beta) \approx 1.24 \times 10^{-25} n_e^2 \Phi V$$

where $n_e$ is the electron density of the line emitting region, $V$ its volume and $\Phi$ the filling factor. We find $0.3 < n_e \times \Phi^{1/2} < 40$. The larger values for $n_e \times \Phi^{1/2}$ are found for 3C 49 and 3C 138, for which the line flux is produced in a region much smaller than the radio size. Excluding these two objects, the upper limit on $n_e \times \Phi^{1/2}$ is $\approx 4$.

As shown by Fanti et al. (1995), if the external medium is clumpy, it is the volume averaged density $n_{sm} = n_e \times \Phi$ which is appropriate in confining the radio source. The value of $n_e^2 \times \Phi$ determined using equation (3) are such that, for $\Phi < 10^{-2}$, $n_{sm}$ is too small to trap the CSS. Conversely, if we take a representative gas density of $n_e \approx 10^3$, determined directly for a few objects using the [SII] doublet (Eracleous and Halpern, 1993), we get $\Phi \approx 10^{-5}$ and $n_{sm} \approx 10^{-2}$, at least two orders of magnitude less than what needed by the "frustration scenario".

Finally, we note that a cool ambient medium sufficiently dense to confine the radio source would also be optically thick to ionizing photons. The required column density is $\geq 2 \times 10^{22}$ cm$^{-2}$, which for neutral hydrogen, corresponds to a Lyman limit optical depth $\sim 10^5$. Few ionizing photons would escape the confining medium and we would not, therefore, expect to see line emission extending significantly beyond the radio source as is the case in 4 of the 5 sources for which we have obtained pointed observations.

We conclude that our HST data favour the model in which CSSs are the young phase of the large size radio sources.

9. Is there any radio-optical continuum alignment effect?

Recently, de Vries et al. (1997) found a strong alignment effect in broad band HST images of CSS at all redshifts. The off-band images obtained as part of the pointed observations allow us to study the genuine continuum morphology of these sources and therefore to explore the origin of their findings. In fact the LRF images isolate a spectral region free of emission lines, 100 Å wide centered in rest frame wavelength range 5400 - 5500 Å. The contour maps of these five continuum images are given in Fig. 8. In the same figures we also mark the orientation of the radio axis. The
lower contours correspond to a surface brightness of $1 - 4 \cdot 10^{-17} \text{ergs}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$; these reference values translate approximatively into a brightness limit of 20 - 22 mag arcsec$^{-2}$ in the V band.

Three of these sources are identified with QSO’s and the host galaxy is only marginally detected: in 3C 147 the lower brightness regions are slightly elongated along NS; in 3C 48 the diffuse extended emission appears to be oriented at PA $\sim -30^\circ$; the host galaxy of 3C 277.1 is essentially circular.

Conversely, in the radio galaxies 3C303.1 and 4C 12.50 the stellar light is clearly visible: in the first case it is highly elongated in the NS direction; the case of 4C 12.50 is more complex due to the presence of a nearby companion and of a common diffuse halo. In the inner regions the isophotes are asymmetrical, being more extended, in both galaxies, toward the side opposite to the companion.

The comparison between the radio and the optical continuum axis is not straightforward since, in most cases, the optical structure is essentially circular. In 3C 303.1, however, there is a clear misalignment ($\sim 40^\circ$) between radio and optical structure. The optical continuum structure is not elongated in the direction of the radio axis in any of our sample.

A possible explanation for these contrasting results might be the relative depths of the two set of data; however our longer exposure times ($\sim 1200$ s) with respect to the snapshot observations compensates largely for the reduced efficiency of the linear ramp filter when compared to the broad F702W filter.

We conclude that broad band images are in most cases heavily contaminated by line emission which, as we discuss in the previous sections, is indeed aligned with the radio structure. This interpretation is strongly supported by the comparison of the images for two objects which are in common between our and De Vries sample (3C 277.1 and 3C 303.1) for which a close radio/optical alignment is seen in the broad band images. By separating line and continuum contribution it is clear that only the line emission is aligned with the radio structure. Similarly, the elongated optical structure (closely aligned with radio axis) seen in the broad band images of 3C 268.3, 3C 305.1 and 3C 343.3 is cospatial with the emission line region as revealed by the narrow band images, suggesting that line emission is also dominating in these cases.

10. Summary and conclusions

In this paper, we analyzed narrow band HST images of eleven CSS radio sources. In all but one of the targets (3C 49) line emission has been detected and only in the case of 3C 138 is it unresolved at the HST resolution. As is generally observed in extended radio galaxies a large fraction (between 30% and 90%) of the line emission originates within a few kpc of the active nucleus.
In six galaxies the radio emission is sufficiently extended that a comparison can be drawn between radio and optical morphologies. The line emission has an elongated jet-like structure aligned with the radio axis. It is likely that this connection between the radio and optical emission is produced by the interaction of the jets with the ambient medium, in a similar way to that observed in Seyfert NLR. This interpretation is also supported by the very broad and flat topped line profiles commonly observed in CSS. Measuring the velocity and the size of the expanding line emitting region provides a unique tool for estimating dynamical timescales for these sources.

However, in four out of five of the sources for which deep observations are available the line emission extends well beyond the size of the radio source, up to a radius of 10 to 30 kpc. The gas responsible for this extended emission is aligned with the radio axis and is localized in well defined elongated structures confined to "broad cones" covering angles which vary between 30° and 110°. Although the origin of the arc structures is unclear, their spatial distribution suggests that they are illuminated by an anisotropic radiation field. This interpretation is supported by "photon counting" arguments. The unresolved continuum sources seen in Broad Line CSSs provide enough photons to ionize the ENLR. Conversely, in Narrow Line CSSs there is a clear photon deficit which indicates that the nucleus is hidden to our direct view, in agreement with the AGN unified scheme.

In no source do we see a bow shock shaped emission line regions enshrouding the radio lobes (commonly observed in Seyfert galaxies) which are expected to form if CSS are trapped by a dense external medium. The question remains if their earlier evolution was significantly affected by the environment or if the smaller CSS are still frustrated. However, the average densities of ionized gas derived from our images are at least two orders of magnitude less than those needed by the "frustration scenario". Our data therefore support the alternative model in which CSSs are the young phase of the large size radio sources. Future kinematic studies of the gas should allow determination of dynamical timescale in the manner used by Capetti et al. (1998) for Seyfert galaxies.

Pure continuum images are available for five CSSs. No alignment between radio and continuum emission is found. The alignment effect seen in broad-band HST images is due to line contamination which, unlike the continuum, is indeed aligned with radio emission.

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REFERENCES


McCarthy, P. J., 1988, PhD. Thesis California University Berkeley


Osterbrock, D. E., Astrophysics of Gaseous Nebulae, Freeman, 1974

This preprint was prepared with the AAS LATEX macros v4.0.
Fig. 1.— Narrow off-band and on-band (left and right top panel) images of 3C 48. The off-band image was scaled to reproduce the continuum contamination in the on-band image. In order to evidence lower brightness line features a higher contrast line image is presented in the bottom left panel. On the bottom right panel we reproduce the Merlin radio image from Wilkinson et al. 1991. Given the small extension of the radio emission it is presented enlarged eight times with respect to the HST images.

Fig. 2.— Same as Fig. 1 for 3C 147. Narrow off-band and on-band (left and right top panels), high contrast on-band image (bottom left) and VLA radio image, taken from van Breugel et al. 1992 (bottom right).

Fig. 3.— Same as Fig. 1 for 3C 277.1. Narrow off-band and on-band (left and right top panels), high contrast on-band image (bottom left) and VLA radio image, taken from Akujor et al. 1995 (bottom right).

Fig. 4.— Same as Fig. 1 for 3C 303.1. Narrow off-band and on-band (left and right top panels), high contrast on-band image (bottom left) and Merlin radio image, taken from Sanghera et al. 1995 (bottom right).

Fig. 5.— Same as Fig. 1 for 4C 12.50. Narrow off-band and on-band (left and right top panels), high contrast on-band image (bottom left). The VLA radio image, taken from Stanghellini et al. 1997 (bottom right) is enlarged by a factor of 10 with respect to the HST images. The radio core is component A.

Fig. 6.— F702W broad band image (left panels), narrow on-band image (central panels) and the VLA radio images, taken from Dallacasa et al. 1995 and Fanti et al., 1985 (right panels) for 3C 93.1 and 3C 268.3 respectively.

Fig. 7.— F702W broad band image (left panels), narrow on-band image (central panels) and the VLA radio images, taken from van Breugel et al. 1992 and Fanti et al. 1985 (right panels) for 3C 305.1 and 3C 343.1.

Fig. 8.— Continuum images in the rest frame spectral range 5400 - 5500 Å obtained from the pointed observations of 3C 48, 3C 147, 3C 277.3, 3C 303.1 and 4C 12.50. The dashed lines mark the orientation of the radio axis.
Table 1. Log of the pointed observations

<table>
<thead>
<tr>
<th>Name</th>
<th>ID</th>
<th>Redshift</th>
<th>Em. Line</th>
<th>λ On-Band</th>
<th>Exp. Time (s)</th>
<th>λ Off-Band</th>
<th>Exp. Time (s)</th>
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<td>3C48</td>
<td>Q</td>
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<td>[O III]</td>
<td>6845</td>
<td>3500</td>
<td>7500</td>
<td>1100</td>
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<tr>
<td>3C147</td>
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<td>[O III]</td>
<td>7736</td>
<td>3900</td>
<td>8500</td>
<td>1200</td>
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<td>Q</td>
<td>0.321</td>
<td>[O III]</td>
<td>6609</td>
<td>3300</td>
<td>7100</td>
<td>1100</td>
</tr>
<tr>
<td>3C303.1</td>
<td>G</td>
<td>0.267</td>
<td>[O III]</td>
<td>6344</td>
<td>4200</td>
<td>6858</td>
<td>1300</td>
</tr>
<tr>
<td>4C12.50</td>
<td>G</td>
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<td>[O III]</td>
<td>5608</td>
<td>3300</td>
<td>6100</td>
<td>1100</td>
</tr>
</tbody>
</table>

Radio-galaxies are identified as G in column 2, while quasars are marked as Q.

Table 2. Log of the snapshot observations

<table>
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<th>ID</th>
<th>Redshift</th>
<th>Em. Line</th>
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<th>F702W Exp. Time (s)</th>
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<td>280</td>
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<td>[O III]</td>
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<td>300</td>
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<td>3C305.1</td>
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<td>600</td>
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<td>3C343.1</td>
<td>G</td>
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<td>[O II]</td>
<td>6522</td>
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<td>300</td>
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Table 3. Radio parameters of the sample

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<th>Name</th>
<th>z</th>
<th>ID</th>
<th>Ang. Size (″)</th>
<th>Lin. Size (kpc)</th>
<th>log $P_{1.7GHz}^1$</th>
<th>log $P_c^1$</th>
<th>$S_c/S_{ext}$</th>
<th>$P_{cm}$</th>
<th>$F_{\text{[OII]}}^2$</th>
<th>$F_{\text{[OIII]}}^2$</th>
<th>Ref.</th>
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<td>.45</td>
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<td>0.62</td>
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<td>7.7</td>
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<td>24.95</td>
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<td>G</td>
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<td>2.9</td>
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<td>&lt;25.0</td>
<td>&lt;.3</td>
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<td>1</td>
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<td>5.7</td>
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<td>26.66</td>
<td>.04</td>
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<td>1.4</td>
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<td>26.19</td>
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<td>.8</td>
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<td>12.0</td>
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<td>1.13</td>
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<td>21.4</td>
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<td>8.4</td>
<td>48.0</td>
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</table>

$^1$Units of the radio power W Hz$^{-1}$

$^2$Units of the line fluxes 10$^{-15}$ erg s$^{-1}$ cm$^{-2}$

$^a$[OII] from Jackson & Browne, [OIII] from Gelderman & Whittle

$^b$[OII] from Wills et al., [OIII] from Gelderman & Whittle


Table 4. CSS photometry

<table>
<thead>
<tr>
<th>Name</th>
<th>Total [O III] flux$^1$</th>
<th>Nuclear [O III] flux$^1$</th>
<th>Nuclear continuum flux$^2$</th>
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<td>Satur.</td>
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<td>8</td>
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</tr>
<tr>
<td>3C277.1</td>
<td>38</td>
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<td>0.19</td>
</tr>
<tr>
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<tr>
<td>4C12.50</td>
<td>33</td>
<td>28</td>
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</tbody>
</table>

$^1$Units of the line fluxes 10$^{-15}$ erg s$^{-1}$ cm$^{-2}$

$^2$Units of 10$^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$
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