The host galaxies of Compact Steep Spectrum and Gigahertz-Peaked Spectrum radio sources

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I will review some of the developments in studies of the host galaxy properties of Compact Steep Spectrum (CSS) and Gigahertz-Peaked Spectrum (GPS) radio sources. In contrast to previous reviews structured around observational technique, I will discuss the host galaxy properties in terms of morphology, stellar content and warm gas properties and discuss how compact, young radio-loud AGN are key objects for understanding galaxy evolution.

1 Introduction

In recent years it has become increasingly clear that AGN play a key role in galaxy evolution, in particular the way in which AGN and its host galaxy interact (e.g. Silk & Rees 1998; Fabian 1999; di Matteo et al 2005). A key time to study the impact the AGN will have on its host galaxy, and how the properties of the host galaxy will influence the AGN, is during the early stages of evolution. As discussed in the papers listed above, among others, after relocating to the centre of the galaxy after the merger, the central black hole will grow rapidly through merger-induced accretion, eventually ‘switching-on’ and becoming a quasar. The merger will deposit large quantities of gas and dust into the nuclear regions, essential to fuel the young AGN, and this must eventually be shed through outflows and winds. However, much of this initial, rapid growth phase will be obscured from view at optical wavelengths by the dense natal cocoon.

Cue the Compact Steep Spectrum (CSS) and Gigahertz-Peaked Spectrum (GPS) radio sources. Now believed to be small due to evolutionary stage, rather than confined and frustrated old sources (e.g. Fanti et al. 1990; Fanti et al. 1995; Owsianik et al. 1998; Murgia et al. 1999), the compact radio sources provide a unique tool for pinpointing young, recently triggered AGN.

Until recently, most effort has focused on the AGN and its radio jets, particularly in the radio band. However, the host galaxies can provide a number of key results, important for both understanding compact radio sources themselves and how they fit in to the bigger picture. Through deep optical spectroscopy with 4-m and 8-m class telescopes, it is possible to study both the emission lines and the near UV-optical continuum emission to search for signatures of AGN-host galaxy interaction and probe the stellar populations & star formation history.

In these proceedings, I give a brief overview of some of the recent developments in studies of compact radio source host galaxy properties. Instead of focussing on observation wavebands and techniques, we now know enough to discuss the various properties in terms of physically meaningful groups, namely the overall system morphology, the stellar and gas content and evidence for AGN-feedback.

2 Host morphology

One of the most basic and easily determined properties of the host galaxies is morphology. Over the last 20 years, a number of broad band imaging studies have been carried out (e.g. Gelderman & Whittle, 1994; O’Dea et al. 1996 & references within). From these studies it is clear that all CSS hosts (Geldermand & Whittle 1994), and the majority (~60%) of GPS hosts (O’Dea et al. 1996) show evidence for recent interactions and/or mergers (e.g. tidal tails, double nuclei, distorted isophotes and arcs, shells and knots of emission) in which at least one of the galaxies involved is gas-rich (Stanghellini 1993). What appear to be companion galaxies are also commonly observed. The results for compact radio sources are consistent to those found for studies of powerful radio galaxies (e.g. Heckman et al. 1986; Smith & Heckman 1989), in particular the hosts of FR II radio sources (O’Dea 1998). Figure† shows some recent optical images of two compact radio sources.

In the past, much effort has gone into classifying hosts as ‘galaxies’ or ‘quasars’ and treating them as discrete samples. This classification should be used with caution for two reasons. First, if we believe in unification, all compact (young) radio sources should be similar objects and the host galaxy classification will only depend on viewing angle. Second, as discussed above, the majority of CSS/GPS sources show

Note, some extended radio sources may appear compact due to projection effects but should only account for ≤25-30% of the identified compact radio sources (Fanti et al. 1990)
evidence for a recent merger or interaction which will have injected a significant amount of gas and dust into the circumnuclear regions. This will obscure the young, recently triggered AGN during the early stages of its evolution (e.g. Silk & Rees 1998; Fabian 1999). Given this, it is likely that we may not be able to see directly into the nucleus in compact (young; e.g. Fanti et al. 1990) radio sources and could mistakenly classify a young ‘quasar’ as a ‘galaxy-type’ host (e.g. PKS 1549-79; Holt et al. 2006).

3 Stellar content

To date, the only systematic studies of the stellar content of the host galaxies of compact radio sources have used optical and/or near-IR imaging (among others: Snellen et al. 1996a,b, 1998; O’Dea et al. 1996; de Vries et al. 1998, 2000, de Vries 2003). Using colours to estimate the broadband SEDs (R,J,H,K), these studies find the colours of both CSS and GPS sources to be consistent with old stellar populations (OSPs; $z_{\text{formation}} \gtrsim 5$), typical of passively or non-evolving elliptical galaxies. Similar results were found in the comparison samples of FR IIs.

Given the large number of CSS and GPS sources displaying evidence for interactions (see Section 2), and knowing that gas-rich mergers can also trigger starbursts, it is surprising that evidence for this was not observed in the stellar populations. This mis-match in results was noted by de Vries (2003) but was explained as observing ‘the first of many interactions’.

However, it has been known for sometime that, when bluer rest-frame colours are considered, many radio galaxies show ultraviolet (UV) excesses compared to normal, passively evolving elliptical galaxies (e.g. Lilly & Longair 1984; Smith & Heckman 1989). The active nucleus will clearly contribute to the UV light, through one or more processes (e.g. direct and/or scattered light from the AGN, emission lines and nebular continuum; e.g. Tadhunter et al. 2002 and references within). However, recent studies have shown that, by taking particular care to account for all of the activity-related components, it is possible to use spectral synthesis modelling techniques across the entire optical rest-frame SED to reveal the presence of young stellar populations (YSPs) in radio galaxies (e.g. Holt et al. 2007 and references within).

As part of the above studies, young and intermediate age stellar populations have been found in 8 compact radio sources including both CSS and GPS sources (PKS 0023-26, PKS 2135-209, PKS 1345+12, 3C 213.1 & 9C J1503+4528, a compact flat spectrum source (PKS 1549-79) and extended radio sources with a second, smaller-scale compact core radio source (3C 236 & 3C 459). The key results are:

- **Young stellar populations:** few Myr - 1 Gyr. Some sources are clearly in the first throes of activity (very young YSP) whilst others may be re-triggered AGN? (older YSP); Wills et al. (2008). The YSPs are often significantly reddened (Holt et al. 2007).

- **The starbursts are galaxy wide events.** In sources which are spatially resolved, the UV excess is extended (Holt et al. 2007; see also HST UV imaging by Labiano et al. 2008). In some sources, extended apertures have been modelled showing clear evidence for YSPs (Tadhunter...
Fig. 2 Results of SED modelling to the nucleus of the southern CSS source PKS 0023-26 taken from Holt et al. (2007). Top plot: The black line traces the rest frame nuclear spectrum which has been corrected for Galactic extinction and the nebular continuum (which accounts for 22.5% of the flux at 3540-3640Å) has been subtracted. Overplotted is the best fitting model (red line) comprising a 12.5 Gyr OSP and a 0.03 Gyr YSP, reddened by a foreground screen with E(B-V) = 0.9. The purple boxes show the location of the bins used for fitting and the histogram on the x-axis shows the residuals of the fit by bin. Bottom left: Contour plot of the reduced chi-squared ($\chi^2_{\text{red}}$) space for combinations of YSP age & reddening – the minimum highlights the better fits. Bottom right: Once the best fits are identified using the whole SED and $\chi^2_{\text{red}}$ contour plot, detailed comparisons are made between the data (solid line) and models (dotted line) using the stellar absorption features, particularly Ca H+K and the Balmer lines.

et al. 2005) including very young Super Star Clusters (SSCs) in the haloes of some objects (Rodriguez Zaurin et al. 2007).

- Prolific star formation. Overall, the YSPs account for few-100% of the stellar mass (Holt et al. 2007). Some of the compact radio sources are also classified as ULIRGs.

4 Gas content

Another major component of the host galaxies is gas and dust. As discussed above, the majority of CSS/GPS sources show evidence for recent mergers/interactions in which at least one of the galaxies was gas rich. Hence, large quantities of gas and dust will be deposited in the circumnuclear regions. The gas may be split into different phases (cold/warm/hot). In this review, I will focus on the warm (optical emission line) gas, discussing the kinematic properties, physical conditions and dominant ionisation mechanism(s). For discussions on the cold and hot gas, readers should refer to other contributions in these proceedings (e.g. Fanti, Orienti, Morganti, Siemiginowska).

4.1 Outflows

In 1994, Gelderman & Whittle reported that the nuclear emission lines in a sample of 20 CSS sources were strong, with broad and structured [O III]λ5007 profiles which may be consistent with strong interactions between the radio source and the ambient gas. However, it was not until 2001 that unambiguous evidence for outflows in the emission line gas were found in the southern compact radio source PKS 1549-79 (Tadhunter et al. 2001).

Tadhunter et al. (2001) reported that in PKS 1549-79, the high ionisation lines (e.g. [O III]λλ4959,5007) were both significantly broader (FWHM$_{[\text{O III}]} \sim 1350$ km s$^{-1}$ compared to FWHM$_{[\text{O I}]} \sim 640$ km s$^{-1}$) and blueshifted (v $\sim 600$ km s$^{-1}$) with respect to the low ionisation lines (e.g. [O II]λ3727). Combined with their other data, they interpreted this as the spectral signature of an outflow in the
emission line gas, driven by the young, small, expanding radio jets (see Figure 2 in Tadhunter et al. 2001).

The discovery of the outflow in PKS 1549-79 triggered a detailed study of the emission line gas in a sample of 14 compact radio sources (Holt 2005; Holt et al. 2008a). Careful modelling of the narrow extended line emission allows the systemic velocity to be accurately measured (Figure 3). In the nuclear apertures, the lines are significantly broader and often require multiple Gaussian components. Combined with the accurate systemic redshifts, it is clear that in 11/14 sources, the broader components are significantly blueshifted, tracing fast outflow

\[ v > 2000 \text{ km s}^{-1} \] in the emission line gas (Holt et al. 2008a). The most extreme example is observed in the GPS source PKS 1345+12 (\( v \sim 2000 \text{ km s}^{-1} \); see Figure 3 and Holt et al. 2003). O’Dea et al. (2002) also report fast (\( v \sim 300-500 \text{ km s}^{-1} \)) outflows in 3 CSS sources from HST/STIS spectroscopy, 2 of which are also in the sample of Holt et al.

Whilst the samples are small, it is clear that the nuclear kinematics in compact radio sources are more extreme than in extended radio sources (see Figure 3 and Holt et al. 2008a). This trend extends within the sample – the smallest (GPS) radio sources tend to have the most extreme outflow velocities. However, radio source orientation may also play a role (Holt et al. 2008a).

Whilst the expanding radio jets provide a convenient driving mechanism for the observed nuclear outflows, it is important to test this scenario. Using emission line ratios and diagnostic diagrams, it is possible to establish the dominant ionisation mechanism of the gas. For their sample of 14 compact radio sources, Holt (2005) & Holt et al. (2008b) found that, whilst the nuclear narrow components (at the systemic velocity) were typically photoionised by the AGN, the broader, blueshifted components were more consistent with shock ionisation, with fast velocities (\( v_{\text{shock}} > 300 \text{ km s}^{-1} \)) and a pre-photoionised (precursor) component. Similar results were found by Labiano et al. (2005) for their sample of 3 CSS sources with HST/STIS (2 of which are in the Holt et al. sample).

A key advantage of emission line outflows over absorption line outflows is that, in addition to kinematics etc from spectroscopy, the outflowing regions can be directly imaged to reveal the size, location and morphology. Narrow band HST imaging (e.g. [O II] and/or [O III]) has shown that, in CSS sources, the optical line emission is co-spatial with, and strongly aligned with, the radio source at all redshifts (e.g. de Vries et al. 1997, 1999; Axon et al. 2000; Priyon et al. 2008) – see Figure 4. This is in contrast to extended radio sources in which the alignment is only observed at \( z > 0.6 \). Batchelor et al. (2007) have also attempted to image the emission line outflow in the GPS source PKS 1345+12 and the compact flat spectrum radio source PKS 1549-79 (see Figure 5). Whilst the radio and optical line emission are clearly co-spatial, the scales are too small to give more than a tentative suggestion that the line emission is elongated along the radio axis. Hence, whilst in the larger CSS sources, there is a clear argument for jet-driven outflows but in the smaller GPS sources, it is impossible to distinguish between AGN-winds and jet-driven outflows.

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2 The blueshifted components are thought to be outflows rather than inflows using reddening arguments. See Holt et al. 2003 for a detailed argument.
4.2 Physical conditions

It is clear that, in order to trigger and fuel nuclear activity, large amounts of gas and dust must be deposited into the circumnuclear regions, whatever the triggering mechanism. For compact radio sources, an ongoing debate has been whether there is sufficient material in the nuclear regions to confine and frustrate the radio source or whether small scale radio jets indeed represent an early evolutionary stage. It is therefore important to determine the physical conditions of the gas, in particular the gas density and mass.

Using emission line ratios, we can make the following general statements about the circumnuclear gas in compact radio sources:

– **Significant reddening in some sources, not in others.** Reddening can be measured using the Balmer lines (Hα, Hβ etc). In some sources, large reddening is measured (up to E(B-V) = 2.0 in the NLR) which can increase with component FWHM in a particular source, as in PKS 1345+12 (Holt et al. 2003; Holt et al. 2008b). In general, the reddening measurements are not significantly different to those for extended radio sources (e.g. Morganti et al. 1997; Labiano et al. 2005; Holt et al. 2008b). The measurements of large reddening, particularly in the broader components, has strengthened the interpretation of the blueshifted line emission as outflows rather than inflows. Whilst the NLR typically shows evidence for low-moderate extinction, the nucleus itself can still be much more highly extinguished at optical wavelengths (e.g. PKS 1549-79; Holt et al. 2006).

– **Large gas densities.** The electron densities are high, typically n_e > few 1000 cm$^{-3}$ (Holt et al. 2003,2008b). Unfortunately, the line profiles are highly complex, precluding accurate measurements using the traditional [S II]λ6716/λ6731 ratio. Work is currently underway to measure the gas densities using alternative diagnostics (Holt et al. 2009).

– **High gas temperatures.** Electron temperatures are estimated to be T_e ~ few × 10$^4$ K, although line measurements suffer from similar issues to those discussed above (Holt 2005; Holt et al 2008b).

– **Mass of the warm gas.** Warm gas masses can be estimated using the luminosity of Hβ and the estimated electron densities. To date, this has only been estimated for the GPS source PKS 1345+12 as $M_{gas} < 10^6$ M$_\odot$ for the line emitting gas.

5 The bigger picture

The results above, combined with previous work, are consistent with the following picture:

1. A major merger occurs where at least one galaxy is gas rich (c.f. observed morphologies). This merger deposits a dense and dusty natal cocoon (c.f. large measured densities and reddening along with the compact radio source & proto-quasar PKS 1549-79 in which the quasar is totally obscured at optical wavelengths).

2. Early on in the merger, a large burst of star formation is triggered in the host galaxy (c.f. detection of YSPs in several compact radio sources).

3. At some point after the onset of the merger, the nuclear activity & radio source are triggered (c.f. age of
the YSPs and the age of the radio source from kinematical and synchrotron spectral ageing measurements; \( t_{\text{radio}} < 10^7 \) years).

4. As the radio source evolves, the small-scale jets expand through the natal cocoon, driving outflows in the emission line gas (c.f. fast outflows, high temperature and evidence for jet-cloud interactions/shock-ionisation).

5. Eventually the AGN will shed its cocoon, starving the nucleus and the circumnuclear starburst (c.f. we observe ‘naked quasars’ and there is no current evidence to suggest there is sufficient gas in the nuclear regions to confine and frustrate the radio source).

6. In at least some sources, after a period of quiescence, nuclear activity is restarted (e.g. double-double sources and the discovery of faint, diffuse, extended radio emission around a number of compact radio sources (e.g. Stanghellini et al. 2005).

With the observations to date, we have been able to form an evolutionary scenario which fits in well with galaxy evolution in general. However, there are still some uncertainties which need to be addressed. Whilst morphology/merger evidence is observed in all CSS sources, it is not observed in all GPS sources (~60% show evidence for morphological disturbance). This leads us to question whether this is due to previous data quality (many of the GPS imaging results are at least 10 years old and may be improved with larger telescopes) or whether an alternative triggering mechanism is required for some GPS sources. Are these sources undergoing recurrent activity? Or a different accretion mode? – see e.g. Tasse (2008), Best et al. (2005) for discussions on hot/cold accretion modes for ‘radio-mode’ and ‘quasar-mode’ AGN.

The stellar population studies on radio galaxies, including a few CSS/GPS sources, have now brought into question previous work suggesting the host galaxies of CSS/GPS sources were passively or non-evolving elliptical galaxies. The past studies included objects which have now been confirmed to have large, young stellar populations (e.g. PKS 1345+12). However, the number of CSS/GPS sources investigated so far is small.

The majority of the CSS/GPS sources included in the studies discussed above are powerful radio sources. However, large numbers of compact radio sources are significantly weaker at radio wavelengths. It is not known how these sources compare to the new results on powerful sources.

Finally, in galaxy evolution simulations, the models require a significant amount of energy for AGN feedback – 5-10% of the accretion energy is required. Fast outflows are now observed in many CSS/GPS sources in both the warm (optical emission lines) and cold (radio; see Morganti et al., these proceedings) gas. However, current estimates of the mass outflow rates for both phases of the ISM fall well below that required for galaxy evolution simulations (e.g. PKS 1549-79; IC 5063, Morganti et al. 2007). Work is currently underway to better estimate the mass outflow rates in compact radio sources.

Hence, much work still needs to be done, especially as compact radio sources are ideal probes of early AGN evolution. More detailed studies are required to enable us to disentangle the interplay between the active nucleus and the host galaxy.

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