Outflows and shocks in compact radio sources

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Abstract. We report some key results from the optical emission line study of a complete sample of compact radio sources. We find strong evidence for jet-driven outflows in the circum-nuclear emission line gas namely: 1) highly broadened and blueshifted emission line components (up to 2000 km s\(^{-1}\)), 2) shock ionised gas (broader, shifted components), 3) consistency in the scales of the emission line gas and the radio source and 4) trends between the maximum outflow velocity and radio source size (and orientation). Full details can be found in Holt (2005).

Key words: galaxies: active; galaxies: ISM; ISM: jets and outflows; ISM: kinematics and dynamics.

1. Introduction

Gigahertz-Peaked Spectrum Radio Sources (GPS: \(D < 1\) kpc) and the larger Compact Steep Spectrum Radio Sources (CSS: \(D < 15\) kpc) account for a significant fraction of the radio source population (\(\sim 40\%\)) although their nature is not fully understood (see e.g. O’Dea 1998 and references therein). Currently, we believe they are young radio sources (Fanti et al. 1995) supported by estimates of dynamical ages: \(t_{\text{dyn}} \sim 10^2\text{--}10^3\) years (Owsianik et al. 1998); and radio spectral ages: \(t_{\text{sp}} < 10^4\) years (Murgia et al. 1999). This is in preference to the frustration scenario where the ISM is so dense, the radio jets cannot escape and the radio source remains confined and frustrated for its entire lifetime (van Breugel 1984).

If compact radio sources are young, we will observe them relatively recently after the event(s) which triggered the activity (e.g. a merger; Heckman et al. 1986). Hence, the circum-nuclear regions will still retain large amounts of gas and dust deposited by the activity triggering event.

During the early lifetime of the radio source, the young small scale radio jets will be on the same scale as this circumnuclear ISM and so will readily interact with it. Hence, one would expect to observe signatures of this interaction namely outflows in the emission line gas and evidence for jet-cloud interactions in the emission line ratios.

Indeed, Tadhunter et al. (2001) reported evidence for fast outflows in the emission line gas in the compact flat spectrum radio source PKS 1549-79. From their low resolution optical spectra, the high ionisation emission lines (e.g. \([\text{O III}]\)) were both broader (FWHM \(\sim 1350\) km s\(^{-1}\)) compared to \(\sim 650\) km s\(^{-1}\)) and blueshifted by \(\sim 600\) km s\(^{-1}\) with respect to the low ionisation lines (e.g. \([\text{O II}]\)). Tadhunter et al. interpreted these unusual kinematics as the signature of the young small scale radio jets expanding out through a dense circumnuclear cocoon of gas and dust giving rise to outflows in the highly ionised emission line gas (see Figure 2 in Tadhunter et al. 2001). More recently, an extreme emission line outflow (up to \(2000\) km s\(^{-1}\)) in the GPS source PKS 1345+12 was reported by Holt, Tadhunter & Morganti (2003).

Hence, we have obtained intermediate resolution (4-6\(\AA\)) optical spectra with good signal-to-noise over a large spectral range (with the WHT, NTT and VLT) to search for such outflows in a statistically complete sample of 14 compact radio sources including 8 CSS, 3 GPS, 2 compact flat spectrum and 1 compact core radio sources (see Holt 2005 for details).

Here, we summarise some of the main results from this study.

2. PKS 1345+12: the most extreme outflow

As discussed in detail by Holt et al. (2003), PKS 1345+12 contains an extreme emission line outflow with two outflowing components – an intermediate component (FWHM \(\sim 1200\) km s\(^{-1}\)) blueshifted by \(\sim 400\) km s\(^{-1}\) and a broad component (FWHM \(\sim 2000\) km s\(^{-1}\)) blueshifted by \(\sim 2000\) km s\(^{-1}\) with respect to the narrowest (FWHM \(\sim 350\) km s\(^{-1}\)) component. The top-left panel in Figure 1 shows the highly complex \([\text{O III}]\)\(\lambda\lambda4959,5007\) emission lines in the nuclear
aperture of PKS 1345+12 and the components required to model the doublet.

By modelling the highly extended (up to \(\sim 20\) kpc) emission line gas, the nuclear narrow component was shown to be consistent with the rest frame of the galaxy. Hence, the broader components trace blueshifted material flowing towards the observer. Through reddening arguments, Holt et al. (2003) argue that this material is on the side of the nucleus closest to the observer and hence traces an outflow in the emission line gas. Indeed, this result is supported by the observation of corresponding velocity components in HI absorption by Morganti et al. (2003).

3. Emission line outflows

In addition to the extreme emission line outflow observed in PKS 1345+12, fast emission line outflows are observed in 11 of the 14 compact radio sources in the sample. Three further examples of highly complex [O III] profiles are shown in Figure 1. To study the significance of the outflows statistically, we define the maximum outflow velocity to be the velocity shift between the systemic velocity (often the narrowest component or, if there are two narrow components, between the two narrow components) and the broadest component taken from the emission line modelling (see Figure 1). Figure 2 shows a pair of histograms comparing the distribution of outflow velocities in this sample of compact radio sources with a complete sample of extended radio sources taken from Taylor (2004).

The distributions are clearly different with the compact radio sources containing more extreme outflows than their extended counterparts. Indeed, this trend is also evident within the sample of compact radio sources – the two highest outflow velocities are observed in some of the smallest (GPS) radio sources. The distributions were tested using a Kolmogorov-Smirnoff test and found to be different at the 99.9% confidence level. Hence, the size of the radio source is clearly important in determining the outflow velocity of the emission line gas.

A more tenuous result links the observed outflow velocity to the orientation of the radio source. Higher outflow velocities are generally observed in radio sources orientated close to the observer’s line of sight whilst radio sources close to the plane of the sky tend to have much smaller outflow velocities. Note, however, for the majority of the sources it was impossible to determine accurate orientations from the radio maps available. However, as orientation is likely to be important to
some degree, the sample was divided into three broad categories (close to the line of sight, close to the plane of the sky and ‘in between’) using the radio map symmetry/asymmetry and whether a radio core was detected or not. The results are plotted in Figure 4.

Finally, two radio sources (PKS 1345+12 and PKS 1549-79) were imaged using ACS on the HST (see Tadhunter et al. 2005, in prep.) revealing the bright emission line regions to be on similar scales to the radio source. Hence, these kinematic results are consistent with the idea that the young, small scale radio sources expand through an enshrouding cocoon giving rise to outflows in the emission line gas.

4. Ionisation mechanisms - the evidence for shocks

Emission line ratios were used to search for further evidence of shock ionisation, a common feature in the extended emission line regions coincident with the radio source around some extended radio sources (e.g. Villar-Martin et al. 1997,1998, Best et al. 2000, Solórzano-Iñarrea et al. 2001, Inskip et al. 2002). In contrast to previous studies, we plot both a larger sample of compact radio sources and also use the kinematic subcomponents rather than treating the lines as single Gaussians. A selection of the diagnostic diagrams presented in Holt (2005) for the nuclear narrow components and nuclear shifted components is shown in Figure 4.

The nuclear narrow components are generally consistent with photoionisation models and are split roughly equally between AGN photoionisation and mixed medium models. However, the nuclear broader components are generally consistent with fast shocks ($v_{\text{shock}} \gtrsim 300 \text{ km s}^{-1}$), often with a strong precursor component. Further evidence for shocks comes from the kinematical results (see above) and the measurement of high temperatures ($T_e \gtrsim 14,000 \text{ K}$) in many sources.

Hence, the nuclear shifted components appear to show similar characteristics to the extended emission line regions with evidence for jet-cloud interactions in extended radio sources. At face value these results appear quite different. However, when the scale of the radio source is taken into account, this further strengthens the idea that compact radio sources and extended radio sources are scaled versions of each other. In extended radio sources, the radio source is on a large scale comparable to the scale of the extended emission line regions, hence shocks are sometimes observed in their EELRs. However, in compact radio sources, the radio jets are small and on the scale of the nuclear regions and so, if shocks are important, they will be observed in the nuclei of compact radio sources.

5. Conclusions

Our results show convincing evidence for the scenario in which compact radio sources are the young relatives of the extended radio sources. As the small scale radio jets expand through the dense cocoon of gas and dust deposited during the triggering event (most likely a merger), they sweep it aside giving rise to outflows in the emission line gas. This study has found several key signatures of this scenario namely:

- fast outflows (up to $2000 \text{ km s}^{-1}$) in the nuclear emission line gas (broad, blueshifted emission line components).
- shock ionised gas (broader shifted components).
- consistency in the scales of the emission line gas and radio source.
trends between the maximum outflow velocity and radio source size and, more tenuously, radio source orientation.

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Fig. 4. A selection of diagnostic diagrams for the nuclear narrow components (top row) and the nuclear shifted components (bottom row). A full discussion is presented in Holt (2005). The data are compared to theoretical models including:
(1) AGN-photoionisation calculated using MAPPINGS. Each line traces a sequence in U, the ionisation parameter ($2.5 \times 10^{-3} < U < 10^{-1}$) for given values of $\alpha$ (-2.0, -1.5 and -1.0) where $F_\nu \propto \nu^\alpha$.
(2) mixed medium photoionisation including both ionisation and matter bounded clouds: $10^{-2} < A_{M/I} < 10$ (Binette et al. 1996).
(3) shock ionisation (pure shocks and models including 50% precursor) for shock velocities $150 < v_{\text{shock}} < 500$ km s$^{-1}$ for a given magnetic parameter ($B/\sqrt{n} = 0, 1, 2, 4$ $\mu$G cm$^{3/2}$) taken from Dopita & Sutherland (1996). The smaller points are for extended radio sources taken from the literature including nuclear regions, EELRs and EELRs with evidence for jet-cloud interactions (see Holt 2005 for details). The open points are for Cygnus A taken from Taylor, Tadhunter & Robinson (2003).