Compact radio sources

Tadhunter, Clive; Morganti, Raffaella; Santoro, Francesco; Bernhard, Emmanuel

Published in:
Astronomische Nachrichten

DOI:
10.1002/asna.20210048

Received: 15 October 2021 | Accepted: 15 October 2021 | Published on: 26 October 2021

DOI: 10.1002/asna.20210048

Astronomische Nachrichten

PROCEEDING

Compact radio sources: Triggering and feedback

Clive Tadhunter[1] | **Raffaella Morganti**[2,3] | **Francesco Santoro**[4] | **Emmanuel Bernhard**[1]

[1]Department of Physics and Astronomy, University of Sheffield, Sheffield, UK

[2]ASTRON, The Netherlands Institute for Radio Astronomy, Dwingeloo, The Netherlands

[3]Kapteyn Astronomical Institute, University of Groningen, Groningen, The Netherlands

[4]Max Plank Institute for Astronomy, Heidelberg, Germany

Correspondence
Clive Tadhunter, Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK.
Email: c.tadhunter@sheffield.ac.uk

Abstract

CSS/GPS objects represent a key stage in the evolution of powerful radio AGN in which the jets are expanding through the denser, kpc-scale ISM in the host galaxies. Therefore, it is important both to understand how such radio AGN are triggered as galaxies evolve and to directly quantify the impact of the outflows induced by the jet-cloud interactions. Here, we show that CSS/GPS sources are likely to be triggered in galaxy mergers, just like powerful radio AGN in general. However, they are both more gas-rich and have higher star formation rates on average than their more extended counterparts. Also, whereas observations frequently show evidence for strong jet-cloud interactions in CSS/GPS in the form of warm outflows, in most cases these warm outflows are unlikely to be energetic enough to affect the star formation histories of the entire host galaxies outside the central kpc. Rather, much of the mass, energy, and momentum of the outflows appear to be tied up in neutral and molecular outflows, which may have a more important impact on the host galaxies. Finally, we consider whether CSS/GPS sources are impostors in flux-limited samples due to the effect of the strong jet-cloud interactions on their radio luminosities.

KEYWORDS

galaxies: active, ISM: jets and outflow, radio lines: galaxies

1 | INTRODUCTION

Once considered an exotic phenomenon, and perhaps not germane to our general understanding of galaxies, over the last 20 years AGN have taken center-stage in models of galaxy evolution. This is because the jets and outflows they drive have the potential to directly affect the star formation histories of galaxies, and explain certain aspects of the general galaxy population, such as the correlations between black hole mass and host galaxy properties (e.g. Kormendy & Ho 2013), and the dearth of galaxies with high stellar masses relative to the mass function of dark matter halos (e.g. Benson et al. 2003; Bower et al. 2006).

The two most frequently discussed forms of AGN feedback are radio mode, in which the large-scale jets and lobes of the expanding radio sources heat the hot ISM/IGM and prevent it from cooling (Best et al. 2005; McNamara & Nulsen 2007), and quasar mode, in which the radiation pressure of the bright, central AGN drives powerful winds that heat and expel the cooler phases of the ISM, thus reducing the star formation efficiency (King & Pounds 2015). However, there is a third form of AGN feedback that is sometimes neglected: the jet-cloud interactions that occur on kpc-scales as the young radio sources expand through the central regions of their host galaxies. Hydrodynamical simulations have shown that such interactions can be as damaging in terms of their impact on star formation as quasar mode, and that the effect is not only confined to the axes of the highly collimated radio sources, but can extend a considerable distance in the perpendicular direction, especially if there is a "flood and channel phase" early in the radio source evolution (Mukherjee et al. 2018; Wagner et al. 2012).

As young radio sources, CSS/GPS objects are particularly important for our understanding of the feedback effect associated with kpc-scale jet-cloud interactions. Clearly, if we are to accurately incorporate this feedback effect into models of galaxy evolution, it is crucial to investigate how, where, and when the CSS/GPS objects are triggered as galaxies evolve, and to use observations to directly quantify the energetic importance of their jet-induced outflows. Here we review what has been learnt over the last decade from optical and infrared observations about the triggering of CSS/GPS objects and the impact of their jets on the host galaxies. In particular, we concentrate on the nine CSS/GPS sources and related objects in the complete $0.05 < z < 0.7$ sample of 2 Jy radio sources described in Dicken et al. (2009).[1] These objects are a representative of luminous ($P_{1.4\ \mathrm{GHz}} > 10^{25}$ W Hz^{-1}), young radio sources in the local universe.

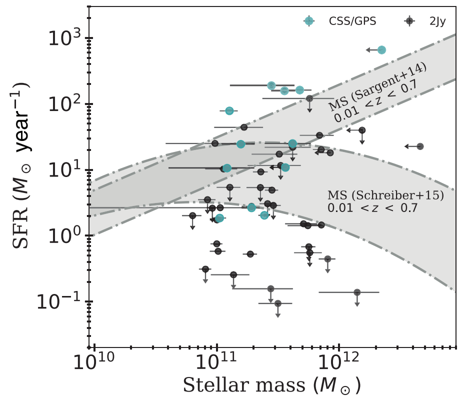

FIGURE 1 SFR (star formation rates) vs stellar mass for the CSS/GPS objects (turquoise points) and extended 2 Jy radio sources (black points). Note that as well as the nine CSS/GPS in the 2 Jy sample, four other nearby CSS/GPS with good far-IR observations are also included (3C48, 3C268.3, 3C305, PKS1345+12). Two determinations of the main sequence for star-forming galaxies from Sargent et al. (2015) and Schreiber et al. (2015) are shown for comparison

2 | HOST GALAXY PROPERTIES AND TRIGGERING

In some aspects at least, the host galaxies of powerful CSS/GPS sources are similar to those of their more extended radio galaxy counterparts: most appear as giant elliptical galaxies with high stellar masses ($M_* \gtrsim 10^{11}$ $M_\odot$: Bernhard et al. 2021), and only 1/9 ($\sim$10%) of the CSS/GPS sources in the 2 Jy sample has a prominent stellar disk (PKS1814-63: Morganti et al. 2011). Moreover, they show a high incidence of tidal features and/or double nuclei, which indicate that the sources have recently ($< 10^{9}$ years) undergone galaxy mergers or interactions: 8/9 (90%) of the CSS/GPS in the 2 Jy sample show such features (Ramos Almeida et al. 2011, 2012). Again, this is similar to powerful extended radio galaxies.

On the other hand, based on deep Spitzer and Herschel observations, the average star formation and cool ISM properties of the CSS/GPS appear to be distinct from those of extended radio sources (Bernhard et al. 2021; Dicken et al. 2012). First considering the star formation properties, in Figure 1 we show a plot of star formation rate against stellar mass for the CCS/GPS and extended radio sources in the 2 Jy sample. In this plot, two determinations of the main sequence for local star-forming galaxies are shown for comparison, and the SFR have been derived using the far-IR continuum luminosities after accounting for the AGN contribution to the far-IR continuum (see Bernhard et al. 2021 for details). It is clear that, on average, the CSS/GPS sources show higher star formation rates (SFR) than extended radio sources, and some fall well above the main sequence for star formation. Indeed, all the highest SFR sources on this plot are CSS/GPS sources.

Further evidence for enhanced star formation in the CSS/GPS sources is provided the fact that they show a relatively high rate of detection of poly-aromatic hydrocarbon (PAH) features in their mid-IR spectra: 8/10 (80%) of the nearby CSS/GPS sources from the combined sample of nearby 2 Jy and 3CR sources studied by Dicken et al. (2012) show such features, whereas they are only detected in 10/48 (21%) of the extended radio sources in the same sample. Similarly, Willett et al. (2010) detect PAH features in 7/8 (88%) of their sample of nearby CSO sources. Note that, whereas the far-IR continuum is potentially subject to contamination by the emission of dust heated by the AGN (e.g. Dicken et al. 2009), which can be hard to correct, the PAH features are widely considered to provide a relatively clean indication of recent star formation activity.

Regarding the cool ISM properties, we can use dust masses derived from Herschel far-IR observations as a proxy for the overall cool ISM reservoirs of the host galaxies (Bernhard et al. 2021; Tadhunter et al. 2014a). Figure 2 compares the dust mass distributions of extended and compact radio sources in the 2 Jy sample. Mirroring the results from the SFR studies, we find that, although

[1]This includes all seven classical CSS/GPS sources with steep radio spectra in the 2 Jy sample at $0.05 < z < 0.7$, along with 3C459, which has steep-spectrum radio core along with a larger-scale FRII morphology, and PKS1549-79, which has a one-sided radio jet but appears to be a genuinely compact radio source that is interacting strongly with the near-nuclear ISM of its host galaxy (Oosterloo et al. 2019).

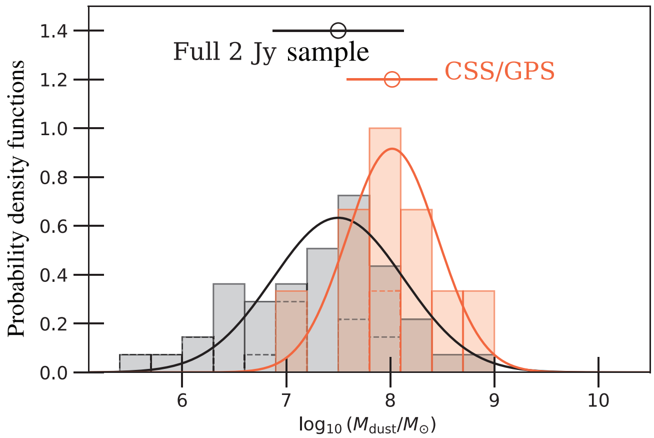

FIGURE 2 Comparison of Herschel-derived dust mass distributions for CSS/GPS and extended radio sources in the $0.05 < z < 0.7$ 2 Jy sample

there is an overlap between the dust mass distributions, CSS/GPS sources have higher dust masses on average than extended sources, and the highest dust mass objects tend to be CSS/GPS sources. In fact, some of the CSS/GPS objects have dust masses that are comparable with those of ultra-luminous infrared galaxies (ULIRGs), which represent the peaks of major, gas-rich mergers. It is also notable that powerful radio AGN in general, but particularly the CSS/GPS sources, have dust masses that are substantially higher than those of typical non-AGN elliptical galaxies in the local universe (Bernhard et al. 2021).

Overall, based on studies of optical morphologies, it is likely that galaxy mergers and interactions are the dominant triggering mechanism for powerful radio sources in the local universe with strong nuclear emission-line activity, including the CSS/GPS sources (Pierce et al. 2021; Ramos Almeida et al. 2011, 2012). However, from the evidence of their SFR and dust masses, it appears that CSS/GPS sources are triggered in mergers that are more major and/or gas-rich than those that trigger extended radio sources.

3 | FEEDBACK

CSS/GPS objects meet the expectation that they should be the sites of major jet-induced feedback in the sense that they show strong observational evidence for jet-cloud interactions. This is manifested in the signs of kinematic disturbance—broad and/or strongly blue-shifted or redshifted components—detected in their optical emission-line profiles (Gelderman & Whittle 1994; Holt et al. 2008; Santoro et al. 2020), which are more apparent in the CSS/GPS than in extended radio sources (Holt et al. 2008), as well as the close alignments between the emission-line structures and the radio sources in some CSS/GPS objects detected in high-resolution HST imaging studies (Axon et al. 2000; Batcheldor et al. 2007; de Vries et al. 1997; Santoro et al. 2020). However, while it is clear that jet-induced feedback is occurring in these sources *at some level*, the energetic significance of the feedback and whether it is truly capable of having a major impact on the star formation in the host galaxy, has been highly uncertain.

Concentrating on the warm outflows, the main dependencies of the mass outflow rate ($\dot{M}$) and kinetic power ($\dot{E}$) on measureable properties are given by the following equations:

$$\dot{M} \propto \frac{L(H\beta)v_{\rm out}}{n_e r}, \quad (1)$$

$$\dot{E} \propto \dot{M}\left(v_{\rm out}^2 + 0.54 FWHM^2\right), \quad (2)$$

where $L(H\beta)$ is the $H\beta$ luminosity, $v_{\rm out}$ is the outflow velocity, n_e is the electron density, r is the outflow radius, and $FWHM$ is the full-width at half maximum of the line profile of the outflowing gas (see Rose et al. 2018; Santoro et al. 2020).

Until recently, most of the key parameters in these equations were highly uncertain. This is because measuring precise electron densities is challenging using the traditional [SII]6731/6717 and [OII]3729/3726 ratios due to blending of the doublet emission lines related to the extreme emission-line kinematics, and a lack of sensitivity of these diagnostics at high densities; the Hβ emission-line luminosity is affected by extinction due to dust in the central regions of the galaxies; and the outflow radius is hard to determine because the emission-line structures are unresolved in seeing-limited, ground-based observations.

In an attempt to overcome these problems, Santoro et al. (2018, 2020) used a novel technique based on the ratios of transauroral [SII] and [OII] lines to determine precise densities and dust extinction values for the CSS/GPS objects in the 2Jy sample. They also used HST narrow-band imaging and ground-based spectroastrometry measurements (see Figure 3) to measure the radii of the emission-line outflows. The results demonstrate that the outflow regions have relatively high electron densities ($10^3 < n_e < 10^5$ cm^{-3}), can suffer a significant amount of reddening and extinction due to dust (up to $E(B-V) \sim 1$), and have radii that are comparable with those of the compact radio sources ($0.06 < r < 2$ kpc). Based on these measurements, Santoro et al. (2018, 2020) determined that the warm outflows in CSS/GPS sources have mass outflow rates and kinetic powers in the ranges $0.1 < \dot{M} < 15$ $M_\odot$ and $4 \times 10^{40} < \dot{E} < 10^{43}$ erg s^{-1}, respectively.

Interestingly, the outflow properties determined for the CSS/GPS sources are similar to those measured for ULIRGs—another class of active object expected to show

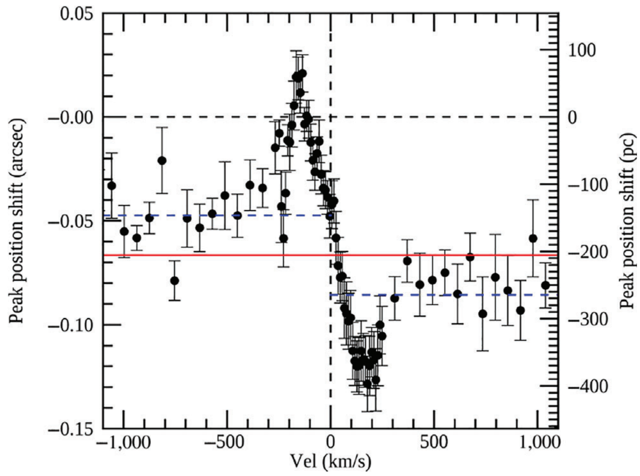

FIGURE 3 Spectroastrometric determination of the warm outflow radius in the archetypal GPS source PKS1934-63. The plot shows the [OIII] spatial centroid position as a function of velocity (see Santoro et al. 2018 for details), and reveals a rotating disk structure at small velocities (S-shaped curve at $|v| < 200$ km s^{-1}) and a bipolar outflow at larger velocities. The red line shows the position of the nucleus

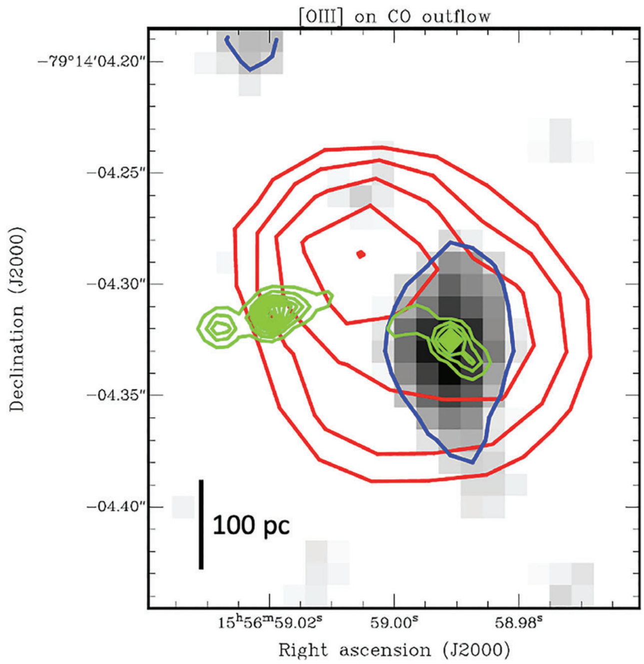

FIGURE 4 The multiphase outflow in the young quasar and GPS source PKS1549-79. The high-velocity CO(1–0) outflow is shown in greyscale and by the blue contour, the warm [OIII] outflow is shown by the red contours, and the 100 GHz radio continuum by the green contours. Note that, whereas the CO outflow is compact and centered on the radio core, the [OIII] outflow is more spatially extended, and centered off-nucleus

particularly powerful outflows—using similar techniques (Rose et al. 2018; Spence et al. 2018; Tadhunter et al. 2018). However, the coupling efficiencies of the warm outflows, which represent the ratios of the outflow kinetic powers to the AGN bolometric luminosities, are relatively modest $\left(0.003 < \dot{E}/L_{\rm bol} < 2\%\right)$, and well below the requirement of some of the hydrodynamic models of galaxy evolution that incorporate AGN feedback (typically 5–10%: Di Matteo et al. 2005; Harrison et al. 2018). Therefore, although the warm outflows associated with the compact radio sources will have a significant effect on the gas on kpc-scales in the central regions of the galaxies, it is unlikely that they are powerful enough to disrupt the cool ISM on larger scales in the host galaxies.

It is important to emphasize, however, that concentrating solely on the warm gas may give a misleading impression of the full impact of the jet-induced outflows. In particular, there is now substantial evidence that AGN-induced outflows are multiphase in character, and that the cooler neutral and molecular gas phases may carry most of the mass and kinetic power of the outflows. For example, using HI 21 cm observations Morganti et al. (2005a, 2005b) have found evidence for neutral outflows in some compact radio sources that are more massive and powerful than the warm outflows in the same objects. Moreover, evidence for massive molecular outflows has also started to emerge for some compact radio sources (Dasyra & Combes 2012; Morganti et al. 2013; Oosterloo et al. 2019). Most notably, the molecular CO outflow detected using ALMA observations of 2 Jy compact radio source PKS1549-79 (Oosterloo et al. 2019: see Figure 4) has a mass outflow rate and kinetic power that are factors of 80× and 20× higher, respectively, than those measured for its warm outflow by Santoro et al. (2020). Although observations of the molecular outflows are challenging, even with ALMA, this is clearly an area that warrants further investigation.

We further note that, although this paper has concentrated on the most luminous CSS/GPS sources selected from bright radio samples, the feedback effect of the jet-cloud interactions is also likely be important for much less luminous compact radio sources. The nearby radio-bright Seyfert galaxy IC5063 is interesting in this regard: It has a compact radio source ($D \sim 1$ kpc) of relative modest radio luminosity ($P_{1.4\rm GHz} = 10^{23.5}$ W Hz^{-1}), yet its jets drive warm, neutral, and molecular outflows that are as massive and powerful as those detected in some more powerful classical CSS/GPS sources (Morganti et al. 1998, 2007, 2015; Oosterloo et al. 2000; Tadhunter et al. 2014b). This is important in the context of statistical studies of emission-line kinematics in large samples of SDSS-selected AGN, which show that the degree of kinematic disturbance measured in the [OIII] emission lines is highest in objects with a similar radio luminosity to IC5063 (Mullaney et al. 2013).[2] Thus, compact radio sources of modest luminosity may be a key source of feedback on the scales of galaxy bulges in nearby galaxies.

4 | ARE CSS/GPS SOURCES IMPOSTORS IN FLUX-LIMITED SAMPLES?

In Section 2, we noted that CSS/GPS sources have higher SFR on average than extended radio sources in the same flux-limited samples. Why is this the case? Potential explanations include the following.

- **Young radio sources are detected closer to the peaks of the merger-induced starbursts than extended radio sources, so their SFR are higher.** This might work if the timescales of the starbursts were much shorter than overall lifetimes of the AGN jet activity. However, in reality, typical starburst timescales (∼100 Myr) are comparable to, or perhaps longer than, the *total* ages of the radio sources (∼10–100 Myr). Therefore, we would expect the starburst activity to be detectable in the hosts of both compact and extended radio sources.
- **The star formation is suppressed by jet-induced feedback over the lifetimes of the radio sources, so younger radio sources show higher SFR.** In this case, signs of the early high SFR should still be visible in optical and far-IR observations over the timescales of the extended radio sources, but this is not observed in most cases.
- **Young radio sources promote jet-induced star formation as they expand through the denser central regions of their host galaxies (e.g. Gaibler et al. 2012; O'Dea & Saikia 2021; Rees 1989).** However, one might expect to be able to detect the vestiges of this star formation on the timescales of extended radio sources. Also, there is a lack of direct observational evidence for this mechanism, apart from a few well-known examples that include Centaurus A (Crockett et al. 2012) and Minkowski's Object (Croft et al. 2006). In the case of Centaurus A, the SFR due to jet-induced star formation is orders of magnitude lower than that of the disk of the host galaxy (Salomé et al. 2016).
- **The link with star formation is due to the fact that most CSS/GPS sources are triggered in unusually dense gaseous environments (Dicken et al. 2012; Gopal-Krishna & Wiita 1991; Morganti et al. 2011; Tadhunter et al. 2011).** In this case, the radio luminosities may be boosted by strong jet-cloud interactions that drive shocks into the radio sources, resulting in particle re-acceleration. This in turn could lead to compact radio AGN of intrinsically lower jet power being preferentially selected in flux-limited samples, so they might be regarded as "impostors" in such samples. The link between CSS/GPS objects and star formation could then arise from the fact that the unusually dense environments in which the sources are triggered are naturally associated with prodigious star formation activity, without the need for jet-induced star formation.

Given that (a) there is clear evidence from their dust masses that CSS/GPS are indeed triggered in unusually gas-rich environments (Bernhard et al. 2021; Tadhunter et al. 2014a), and (b) there is plenty of evidence for strong jet-cloud interactions in these sources (see Section 3), we favor the fourth—impostor—explanation. This is also supported by the fact that there are more compact sources in bright, flux-limited radio sources than expected based on the extrapolation of the number-size relation for extended radio sources (O'Dea & Baum 1997), and by evidence that CSS/GPS sources fall below the correlation between [OIII] emission-line luminosity and radio luminosity defined by extended radio sources (Morganti et al. 2011)—a possible sign that their AGN are intrinsically less powerful. Moreover, where jet-cloud interactions are seen to occur on larger scales in extended radio sources, there is clear evidence for the expected flux boosting in the form of radio knots at the sites of the interactions (e.g. Evans et al. 2008; Fosbury et al. 1998; Tadhunter et al. 2000).

If correct, the impostor idea would have major implications for our understanding of the relationship between compact and extended radio sources in terms of evolutionary scenarios. However, further modelling work is required to demonstrate that the required levels of radio flux boosting can be achieved by strong jet-cloud interactions in dense gaseous environments. Such modelling is also required to investigate whether compact radio sources triggered in dense environments will eventually expand to larger scales be observable as classical extended radio sources.

5 | CONCLUSIONS

CSS/GPS radio sources are key objects for our understanding of the impact of radio jets on the kpc-scale cool ISM in galaxies. Like their most extended radio AGN counterparts, such sources are hosted by massive elliptical galaxies that show evidence for recent galaxy interactions and mergers, but on average their cool ISM masses and SFR

[2] Such intermediate-luminosity radio sources are also likely to be compact: Pierce et al. (2019).

are higher. Therefore, it is not surprising that we see evidence for strong jet-cloud interactions as the young radio sources expand through the central regions of the galaxies. However, the mass outflow rates and kinetic powers of the warm outflows driven by the jet-cloud interactions are relatively modest—capable of ejecting and heating the cool gas in the near-nuclear regions, but perhaps not sufficient to significantly affect the larger-scale gas in the host galaxies. Although it is possible that most of the mass and energy of the outflows is tied up in the cooler ISM phases, further research is required to firmly establish this.

Finally, we note that studies of jet-cloud interactions have tended to focus on the impact they have on the cool gas in the host galaxies; however, their effect on the radio sources themselves has been relatively neglected. Our analysis of cool ISM masses and SFRs of CSS/GPS compared with more extended radio sources provides evidence that their radio luminosities have been boosted by shocks driven into the relativistic plasma by the strong jet-cloud interactions. In this case, some CSS/GPS sources may be impostors in flux-limited samples, affecting our understanding of their relationship with extended radio sources of similar luminosity.

ACKNOWLEDGMENTS

CT, FS, and EB acknowledge support from STFC.

ORCID

Clive Tadhunter https://orcid.org/0000-0002-2951-3278
Raffaella Morganti https://orcid.org/0000-0002-9482-6844

REFERENCES

Axon, D., Capetti, A., Fanti, R., et al. 2000, *AJ*, *120*, 2284.
Batcheldor, D., Tadhunter, C., Holt, J., et al. 2007, *ApJ*, *661*, 70.
Benson, A., Bower, R., Frenk, C., et al. 2003, *ApJ*, *599*, 38.
Bernhard, E., Tadhunter, C., Pierce, J., et al. 2021, *MNRAS* submitted.
Best, P. N., Kauffmann, G., Heckman, T. M., Brinchmann, J., Charlot, S., Ivezić, Ž., & White, S. D. M. 2005, *MNRAS*, *362*, 25.
Bower, R., Benson, A., Malbon, R., et al. 2006, *MNRAS*, *370*, 645.
Crockett, R. M., Shabala, S. S., Kaviraj, S., et al. 2012, *MNRAS*, *421*, 1603.
Croft, C., van Breugel, W., de Vries, W., et al. 2006, *ApJ*, *647*, 1040.
Dasyra, K., & Combes, F. 2012, *A&A*, *541*, L7.
Di Matteo, T., Springel, V., & Hernquist, L. 2005, *Nature*, *433*, 604.
Dicken, D., Tadhunter, C., Axon, D., et al. 2009, *ApJ*, *694*, 268.
Dicken, D., Tadhunter, C., Axon, D., et al. 2012, *ApJ*, *745*, 172.
Evans, D., Fong, W.-F., Hardcastle, M., et al. 2008, *ApJ*, *675*, 1057.
Fosbury, R., Morganti, R., Wilson, W., et al. 1998, *MNRAS*, *296*, 701.
Gaibler, V., Khochfar, S., Krause, M., & Silk, J. 2012, *MNRAS*, *425*, 438.
Gelderman, R., & Whittle, M. 1994, *ApJSS*, *91*, 491.
Gopal-Krishna, & Wiita, P. J. 1991, *ApJ*, *373*, 325.
Harrison, C. M., Costa, T., Tadhunter, C. N., et al. 2018, *NatAs*, *2*, 198.
Holt, J., Tadhunter, C., & Morganti, R. 2008, *MNRAS*, *387*, 639.
King, A., & Pounds, K. 2015, *ARA&A*, *53*, 115.
Kormendy, J., & Ho, L. C. 2013, *ARA&A*, *51*, 511.
McNamara, B., & Nulsen, P. 2007, *ARA&A*, *45*, 117.
Morganti, R., Oosterloo, T., & Tsvetanov, Z. 1998, *AJ*, *115*, 915.
Morganti, R., Oosterloo, T., Tadhunter, C., van Moorsel, G., & Emonts, B. 2005a, *A&A*, *439*, 521.
Morganti, R., Tadhunter, C., & Oosterloo, T. 2005b, *A&A*, *444*, L9.
Morganti, R., Holt, J., Saipalli, L., Oosterloo, T., & Tadhunter, C. 2007, *A&A*, *476*, 735.
Morganti, R., Holt, J., Tadhunter, C., et al. 2011, *A&A*, *535*, 97.
Morganti, R., Fogasy, J., Paragi, Z., Oosterloo, T., & Orienti, M. 2013, *Science*, *341*, 1082.
Morganti, R., Oosterloo, T., Oonk, J., Frieswijk, W., & Tadhunter, C. 2015, *A&A*, *580*, 1.
Mukherjee, D., Bicknell, G. V., Wagner, A. Y., Sutherland, R. S., & Silk, J. 2018, *MNRAS*, *479*, 5544.
Mullaney, J. R., Alexander, D. M., Fine, S., Goulding, A. D., Harrison, C. M., & Hickox, R. C. 2013, *MNRAS*, *433*, 622.
O'Dea, C., & Baum, S. 1997, *AJ*, *113*, 148.
O'Dea, C., & Saikia, D. J. 2021, *A&ARv*, *29*, 3.
Oosterloo, T., Morganti, R., Tzioumis, A., et al. 2000, *ApJ*, *119*, 2085.
Oosterloo, T., Morganti, R., Tadhunter, C., Oonk, R., Bignall, H. E., Tzioumis, T., & Reynolds, C. 2019, *A&A*, *632*, 66.
Pierce, J., Tadhunter, C., & Morganti, R. 2019, *MNRAS*, *487*, 5490.
Pierce, J., Tadhunter, C., Gordon, Y., Ramos Almeida, C., Ellison, S., Grimmett, L., Makrigianni, L., Bessiere, P., Dona Giron, P. 2021, *MNRAS* Submitted.
Ramos Almeida, C., Tadhunter, C. N., Inskip, K. J., Morganti, R., Holt, J., & Dicken, D. 2011, *MNRAS*, *410*, 1550.
Ramos Almeida, C., Bessiere, P. S., Tadhunter, C. N., et al. 2012, *MNRAS*, *419*, 617.
Rees, M. 1989, *MNRAS*, *239*, L1.
Rose, M., Tadhunter, C., Ramos Almeida, C., Rodríguez Zaurń, J., Santoro, F., & Spence, R. 2018, *MNRAS*, *474*, 128.
Salomé, Q., Salomé, P., Combes, F., Hamer, S., & Heywood, I. 2016, *A&A*, *586*, 45.
Santoro, F., Rose, M., Morganti, R., Tadhunter, C., & Holt, J. 2018, *A&A*, *617*, 139.
Santoro, F., Tadhunter, C., Baron, D., Morganti, R., & Holt, J. 2020, *A&*, *644*, 54.
Sargent, M. T., Daddi, E., Béthermin, M., et al. 2015, *ApJ*, *793*, 19.
Schreiber, C., Pannella, M., Elbaz, D., et al. 2015, *A&A*, *575*, 74.
Spence, R. A. W., Tadhunter, C. N., Rose, M., & Rodríguez Zaurín, J. 2018, *MNRAS*, *478*, 2438.
Tadhunter, C., Villar-Martín, M., Morganti, R., Bland-Hawthorn, J., & Axon, D. 2000, *MNRAS*, *314*, 849.
Tadhunter, C., Holt, J., González Delgado, R., et al. 2011, *MNRAS*, *412*, 960.
Tadhunter, C., Dicken, D., Morganti, R., Konyves, V., Ysard, N., Nesvadba, N., & Almeida, C. R. 2014a, *MNRASL*, *445*, L51.
Tadhunter, C., Morganti, R., Rose, M., Oonk, J., & Oosterloo, T. 2014b, *Nature*, *511*, 440.
Tadhunter, C., Zaurín, J. R., Rose, M., et al. 2018, *MNRAS*, *478*, 1558.
de Vries, W., O'Dea, C., Baum, S., et al. 1997, *ApJSS*, *110*, 191.
Wagner, A. Y., Bicknell, G. V., & Umemura, M. 2012, *ApJ*, *757*, 136.
Willett, K. W., Stocke, J. T., Darling, J., & Perlman, E. S. 2010, *ApJ*, *713*, 1393.

AUTHOR BIOGRAPHY

Clive Tadhunter is a Professor of Astrophysics at the University of Sheffield, where he has been based since 1991.

How to cite this article: Tadhunter, C., Morganti, R., Santoro, F., & Bernhard, E. 2021, *Astron. Nachr.*, *342*, 1200. https://doi.org/10.1002/asna.20210048