Mem. S.A.It. Vol. 79, 1205
© SAIt 2008

Memorie della

The importance of sub-relativistic outflows in AGN host galaxies

Clive Tadhunter

Department of Physics & Astronomy, University of Sheffield, Sheffield, S3 7RH, UK
e-mail: `c.tadhunter@sheffield.ac.uk`

Abstract. In the light of recent speculation that AGN have a major impact on the evolution of their host galaxies, I review the observational evidence for energetic outflows around AGN, concentrating in particular on the spatially resolved outflows around radioloud AGN. There is now substantial evidence that the large-scale radio jets have a major impact on the evolution of the hot and warm ISM in the surround galaxy haloes and clusters on a ~5 – 500 kpc scale. However, although clear evidence for warm and cool outflows has also been found on the smaller (<5 kpc) scale of the NLR, these outflows are in general much less energetic than those driven by the radio jets on a larger scale. Indeed, the warm outflows detected in the NLR using both optical emission lines and narrow UV absorption line are generally less massive and energetic than those driven by extreme starbursts in ULIRGs. Apart from the radio jets, the only AGN-induced outflows that come close to matching the requirements of the galaxy evolution feedback models are those detected using the blueshifted X-ray absorption edge features.

Key words. galaxies: active, galaxies: evolution

1. Introduction

Stimulated by the discovery of close correlations between the masses of the supermassive black holes and properties of their host galaxies (Tremaine et al. 2002; Marconi & Hunt 2003), the feedback effect associated with AGN-induced outflows is now routinely incorporated into both semianalytic and hydrodynamic models of galaxy evolution (di Matteo et al. 2005; Bower et al. 2006; Croton et al. 2006). As well as successfully reproducing the black hole/host galaxy correlations, models that incorporate the AGN feedback effect can also explain the high-end shape of the galaxy luminosity function (Benson et al. 2003), which had proved problematic for previous AGN-free models. However, AGN feedback is incorporated into the models as just one of many free parameters that can be tuned to reproduce the observed properties of nearby galaxies. Therefore, is now essential to use observations to directly quantify the impact that AGN have on their host galaxies. In particular: what is the observational evidence for powerful, AGN-induced outflows in the local Universe?

Before reviewing the observational evidence, it is important to consider the nature of the interactions between the AGN and the circumnuclear ISM. There are three main ways in which AGN can interact with their environ-

---

Send offprint requests to: C. Tadhunter

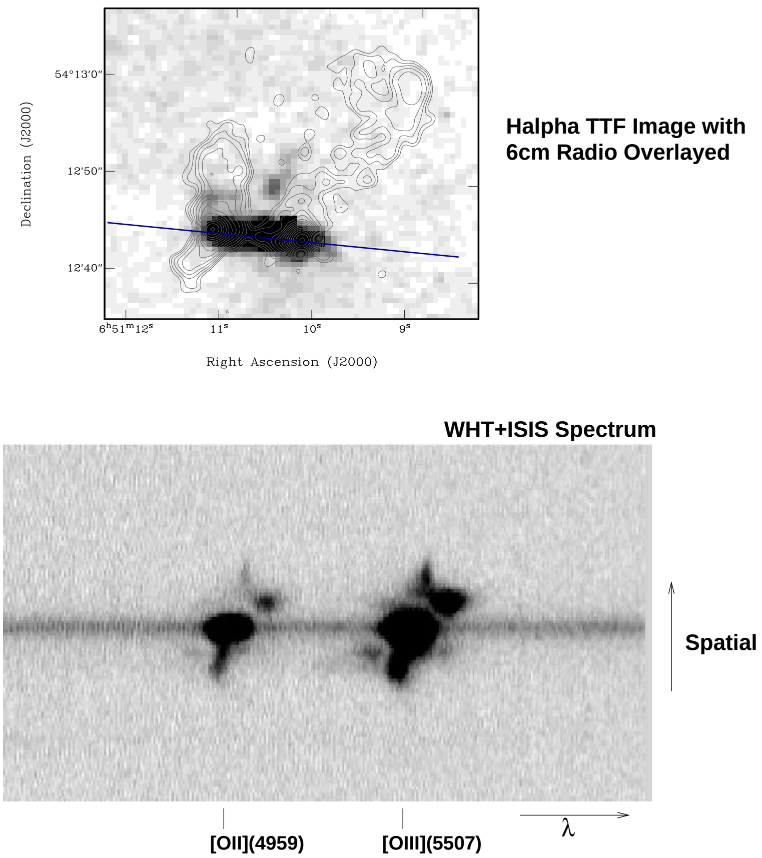

Fig. 1. Jet-cloud interactions in the intermediate redshift radio galaxy 3C171 ($z = 0.238$, see Clark et al. 1998 and Tadhunter et al. 2000 for details). Note the disturbed emission line kinematics present in regions that are actively interacting with the radio lobes, and the more quiescent kinematics at larger radii.

ments: relativistic jets, radiation, and winds. The relativistic jets and radiation fields have similar powers in radioloud AGN: $10^{43} < P < 10^{47}$ erg s^{-1}, corresponding to total energies in the range $10^{57} < E < 10^{62}$ erg integrated over the lifetimes of the AGN. To put these numbers into context, for the most luminous (quasar-like) AGN, the jet powers and bolometric luminosities are comparable with, or larger than, the X-ray luminosities of massive clusters of galaxies, while the lifetime-integrated power outputs are comparable to the total binding energy of the gas in a typical spiral galaxy. Clearly there is plenty of energy available, but what really matters is the coupling between the energy transmitting medium and the ISM in the galaxies. For example, if the ISM in the halo of a galaxy is highly ionized, the prodigious quasar radiation will couple only weakly with the gas. Moreover, the radiation will suffer from geometrical dilution. Therefore, in terms of the impact on the host galaxy evolution, the quasar radiation field is most likely to be important in the inner few kpc where it will ionize the gas and (potentially) drive outflows. On the other hand, the relativistic jets not only couple strongly with all phases of the ISM, but they are also capable of projecting the power of the AGN to scales of hundreds of kpc.

In in this article I will review the observational evidence for AGN-induced outflows, concentrating in particular on the evidence for outflows on the scales of galaxy bulges. Considerable effort has been put into investigating AGN outflows using the narrow absorption lines detected at UV and X-ray wavelengths against the AGN continua of Type 1 AGN. While such studies provide unambiguous evidence for outflows in the form of blueshifted absorption lines in a large proportion (~60%) of nearby Seyfert 1 galaxies (Crenshaw et al. 2003), they suffer from the disadvantage that the spatial locations, geometries and physical conditions are not directly determined. This leads to large uncertainties in the derived mass outflow rates and kinetic powers for the outflows. Therefore I will concentrate on the spatially resolved outflows that have been detected around radioloud AGN in the local Universe, starting with the largest spatial scales and then working inwards.

2. The impact of jets in clusters and galaxy haloes

The exquisite Chandra X-ray images that have recently been obtained for several clusters of galaxies provide clear evidence that the radio jets have a major effect on the energy balance of the hot intercluster medium. For example, Chandra images of the cluster surrounding the powerful nearby radio galaxy Cygnus A show cavities in the hot gas that have been hollowed out by the expanding radio lobes; surrounding the cavities are regions of enhanced emission that have a higher temperature than the intercluster medium at larger radii (Wilson et al. 2006). By assuming that the latter features represent material that has been swept up by the shocks driven by the expanding radio lobes, it is possible to show that the shocks are only mildly supersonic. However, the associated mass outflow rates and kinetic powers in the shock-driven outflows are large: $\dot{M} \sim 10^4$ $M_\odot$ yr^{-1}; $\dot{E} \sim 4 \times 10^{45}$ erg s^{-1} ($\dot{E}/L_{\rm edd} \sim 10^{-2}$).

Although Cygnus A is an unusually powerful radio galaxy by local standards, jet-hollowed cavities have also been found in central cluster galaxies with much lower power radio emission (McNamara & Nulsen 2007). Indeed, some clusters without significant radio jet emission harbour bubble features in the hot gas that are though to represent the relics of past phases of the radio jet activity. Given the large energies associated with the cavities (10^{59} – 10^{62} erg), the radio jets are likely have a major impact on the energetics of the intercluster gas, perhaps explaining the lack of evidence for cooling flows in the X-ray spectra of the clusters. Another interesting feature of these results is that they imply a relatively low efficiency for the conversion of mechanical jet power into radio emission (0.1 – 10% in most cases); the jets can be powerful even in galaxies with relatively puny radio emission. The incorporation of such "radio-mode" feedback into semianalytic galaxy evolution models has proved highly successful (Bower et al. 2006; Croton et al. 2006), and is backed up by statistical studies of radioloud AGN detected in the SDSS surveys which show that a large fraction of the most massive nearby elliptical galaxies have significant radio jet activity (Best et al. 2006). Essentially, the radio-mode feedback affects galaxy evolution by preventing the hot gas from cooling and forming stars. This helps to explain the relative dearth of giant elliptical galaxies in the local Universe (Benson et al. 2003).

As well as the hot intercluster medium, the radio jets also have a major disruptive impact on the denser warm/cool phases of the ISM in radio galaxy haloes. Several spectroscopic studies of the extended emssion line gas detected along the radio axes of nearby radio galaxies show evidence for extreme emission line kinematics in the form of large velocity shifts, line broadening and splitting (Clark et al. 1998, Villar-Martin et al. 1999: see Figure 1). The emission line ratios measured in some of these jet-cloud, or jet-lobe, interactions imply that the gas has been ionized by the jet-induced shocks, rather than the quasar ionizing radiation field (Villar-Martin et al. 1999); such interactions provide a natural explanation

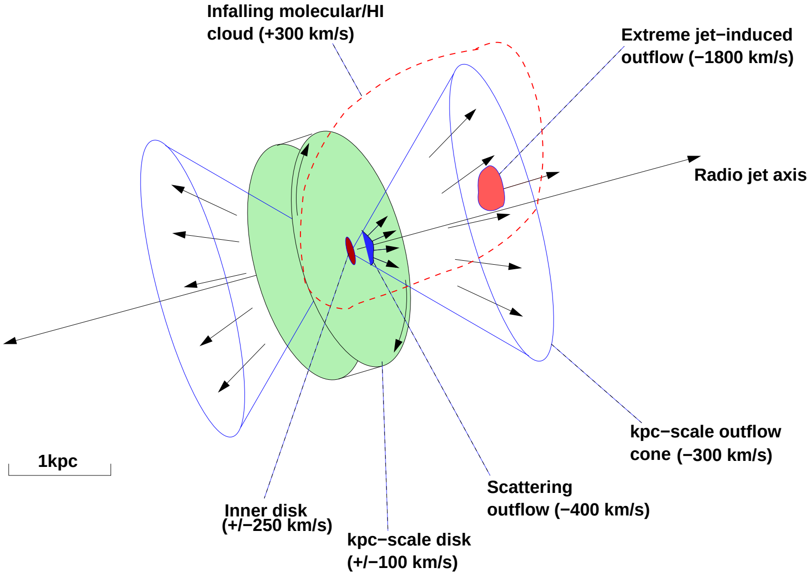

Fig. 2. Schematic illustration of the various kinematic components detected in the archetypal powerful radio galaxy Cygnus A. Negative velocities indicate components that are blueshifted relative to the galaxy rest frame.

for the alignment effect observed in high redshift radio galaxies (Solórzano-Iñarrea et al. 2001). The masses and energies associated with the jet-induced warm outflows are also large ($10^3 < \dot{M} < 10^5$ $M_\odot$ yr^{-1}; $10^{44} < \dot{E} < 10^{46}$ erg s^{-1}; $10^{-3} < \dot{E}/L_{edd} \sim 10^{-1}$: Villar-Martin et al. 1999, Nesvadaba et al. 2006). At the upper ends of the ranges, these large-scale warm outflows are as massive and powerful as those induced by the jets in the hot ISM.

3. Warm outflows in the narrow line region

Although the jet-induced outflows clearly dominate in many radioloud AGN on a scale of 5 – 500 kpc, it is important to consider whether AGN-driven wind components also have a significant impact.

AGN winds are invoked in some hydrodynamical simulations of galaxy evolution in which the AGN activity is triggered by major galaxy mergers of gas-rich galaxies, as gas is driven into the nuclear regions (di Matteo et al. 2005). Eventually the outflows associated with the growing supermassive black holes in the nuclei become sufficiently powerful to drive the remaining gas from the central regions of the remnant, halting further AGN and starburst activity. The latter processes is sometimes termed “quasar mode” feedback, and the models that incorporate it require the kinetic power in the wind to be a relatively large fraction of the available accretion power ($\dot{E}/L_{edd}$ ~0.05 – 0.1: di Matteo et al. 2005), in order to explain the black hole/host galaxy correlations.

Since the AGN winds are likely to be relatively most important in the circumnucler regions, the narrow line region (NLR: $r < 5$ kpc) is an excellent place to search for them. I now consider observations of the NLR in two particularly well-studied radio galaxies: Cygnus A ($z = 0.560$) and PKS1549-79 ($z = 0.152$).

Cygnus A is not only the most powerful extragalactic radio source in the local Universe, but also one of the closest AGN of genuinely quasar luminosity; if AGN winds are important we might expect to find evidence for them in the NLR in Cygnus A. A further important feature of this object is that its geometry and orientation are uniquely well-determined. Moreover, the obscuration of the quasar nucleus by the circumnuclear torus allows a close-up view of the NLR, which is well-resolved and confined to a biconical structure that straddles the nucleus. However, despite the fact that Cygnus A has been studied in detail for more than 50 years, it is only in the last decade that the rest frame of the host galaxy has been tied down sufficiently accurately to allow searches to be made for subtle evidence of AGN winds (Tadhunter et al. 2003; Taylor et al. 2003).

The difficulty with interpreting the emission line kinematics in Cygnus A (and other radio galaxies) is partly due to the overall complexity of the NLR, with several components present, and partly a consequence of patchy dust obscuration. Indeed, using the accurate rest frame determined from near-IR spectroscopic observations, no less that 6 kinematic components have been identified in the NLR of Cygnus A: 3 gravitational, and 3 outflow (see Figure 2). Concentrating on the broad cone outflow component which is most readily identified with the AGN wind, it has proved possible to use density estimates (from emission line diagnostics) along with the excellent geometrical information to determine the properties of the NLR outflow accurately. The results are surprising in the sense that they indicate a relatively modest mass outflow rate ($\dot{M} \sim 5 - 10$ M$_\odot$ yr^{-1}) and kinetic power ($\dot{E} \sim 2 \times 10^{41}$ erg s^{-1}; $\dot{E}/L_{\rm edd} \sim 10^{-6}$), certainly less powerful than the outflows induced in the hot cluster gas by the large-scale radio jets, and several orders of magnitude less powerful than required by the galaxy evolution models. However, it is important to add the caveat that Cygnus A is accreting at a relatively low Eddington rate ($L_{\rm bol}/L_{\rm edd} \sim 3\times10^{-2}$: Tadhunter et al. 2003), but the quasar mode models predict $L_{\rm bol}/L_{\rm edd} \sim 1$.

Whereas Cygnus A may represent the late-time re-triggering of quasar activity, rather than the main event in terms of black hole growth, PKS1549-79 represents a situation much closer to that envisaged in the quasar mode feedback models. Despite the fact that the radio properties of PKS1549-79 are consistent with its jet pointing close to our line of sight, its quasar nucleus is heavily obscured at optical wavelengths, with optical and near-IR measurements indicating a high Eddington ratio (Holt et al. 2006). At the same time, the presence of a NLR outflow is indicated by broad, high ionization emission lines ([NeV], [NeIII], [OIII], [FeVII]) that are strongly blueshifted ($\Delta V \sim 700$ km s^{-1}) relative to the lower ionization emission lines measured in the same spectra (Tadhunter et al. 2001; Holt et al. 2006). The [OIII] outflow is spatially resolved in HST/ACS imaging observations (Batcheldor et al. 2007), and the overall continuum morphology of the object suggests that the activity has been triggered in a major, gas-rich merger. Overall, PKS1549-79 fulfills all the requirements for an object in which the black hole is growing rapidly via merger-induced accretion and simultaneously driving an outflow. However, despite its status as a nearby example of a proto-quasar, the mass outflow rate and kinetic power estimated for the warm outflow in PKS1549-79 on the basis of emission line imaging and spectroscopy are relatively modest ($10^{-1} < \dot{M} < 10$ M$_\odot$ yr^{-1}; $5 \times 10^{40} < \dot{E} < 5 \times 10^{42}$ erg s^{-1}; $10^{-6} < \dot{E}/L_{\rm edd} < 10^{-4}$): similar to the results obtained for Cygnus A, but well below the requirements of the quasar mode feedback models.

It is important to note that, although I have concentrated on two objects that might be considered as extremes of the AGN population, similar results have been obtained for Seyfert galaxies, based on spectroscopic studies of both the emission line gas in the NLR (Veilleux et al. 2005) and the narrow absorption lines detected against the continuum of the Type 1 nuclei of some objects (McNamara & Nulsen 2007). Clearly, existing observations of the NLR in a variety of nearby AGN of different types do not provide a compelling case to support the quasar mode feedback models.

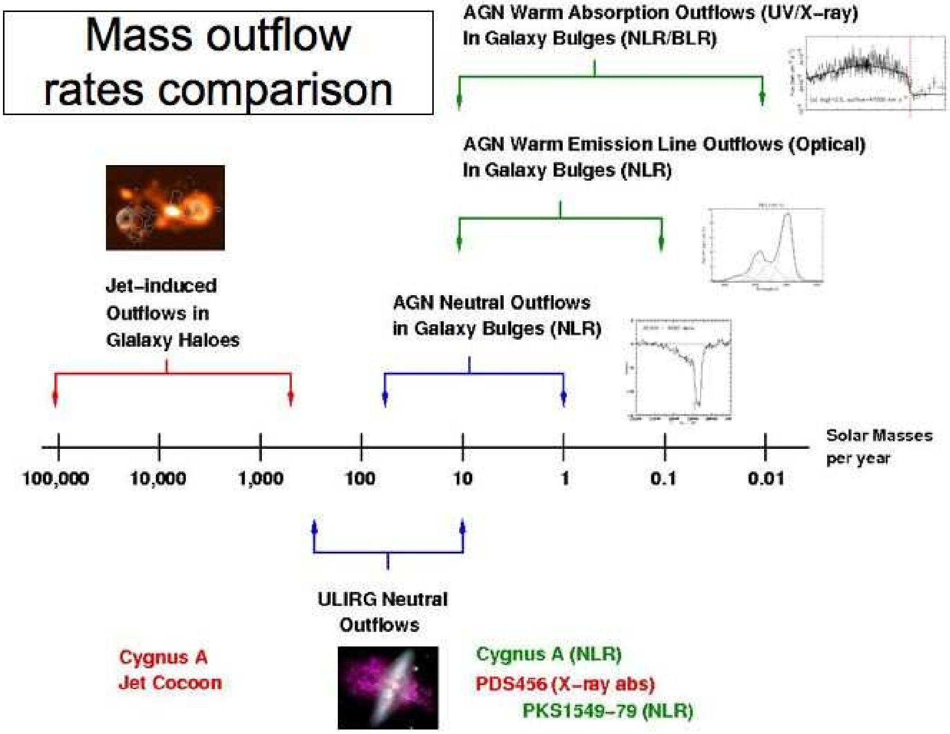

Fig. 3. The mass outflow rates measured for the various types of AGN-induced outflows compared with those measured for the neutral outflows in ULIRGs.

4. Other phases of the ISM

A possible reason for the failure to detect warm NLR outflows as energetic as those required by the galaxy evolution models is that a large fraction of the mass in the outflows is tied up in hotter and/or cooler phases of the ISM that are relatively difficult to detect at optical wavelengths. Considering first the evidence for hotter outflows, recent X-ray satellite observations of a number of nearby AGN have revealed evidence for broad absorption edge features due to highly ionized iron that are blueshifted by ~20,000 – 50,000 km s^{-1} relative to the rest frames of the host galaxies (Pounds et al. 2003; Revees et al. 2003, 2008). The variability timescales of the features suggest that the absorbing gas is located close to the AGN ($r \leq 1$ pc), and, although the associated mass outflow rates are relatively modest ($\dot{M}$ ~10 $M_{\odot}$ yr^{-1}), the kinetic powers estimated for the outflows (scaling as $\sim V_{\rm out}^3$) are large ($\dot{E} \sim 10^{46}$; $\dot{E}/L_{\rm edd}$ ~0.1). Indeed, these warm/hot outflows appear to be as powerful as required by the quasar mode feedback models, although it is important to add the caveat that interpretation of X-ray absorption edge features often involves making assumptions about the radial location, geometry and physical conditions of the outflow region. There also remains the question of what happens to the outflows between the pc-scale of the BLR and the kpc-scale of the NLR; if such outflows truly affect the evolution of the ISM in the host galaxies as a whole, we should expect to find evidence for them in the NLR.

Less obviously, recent radio observations have provided clear evidence for fast *neutral* outflows in the NLR in the form of strongly

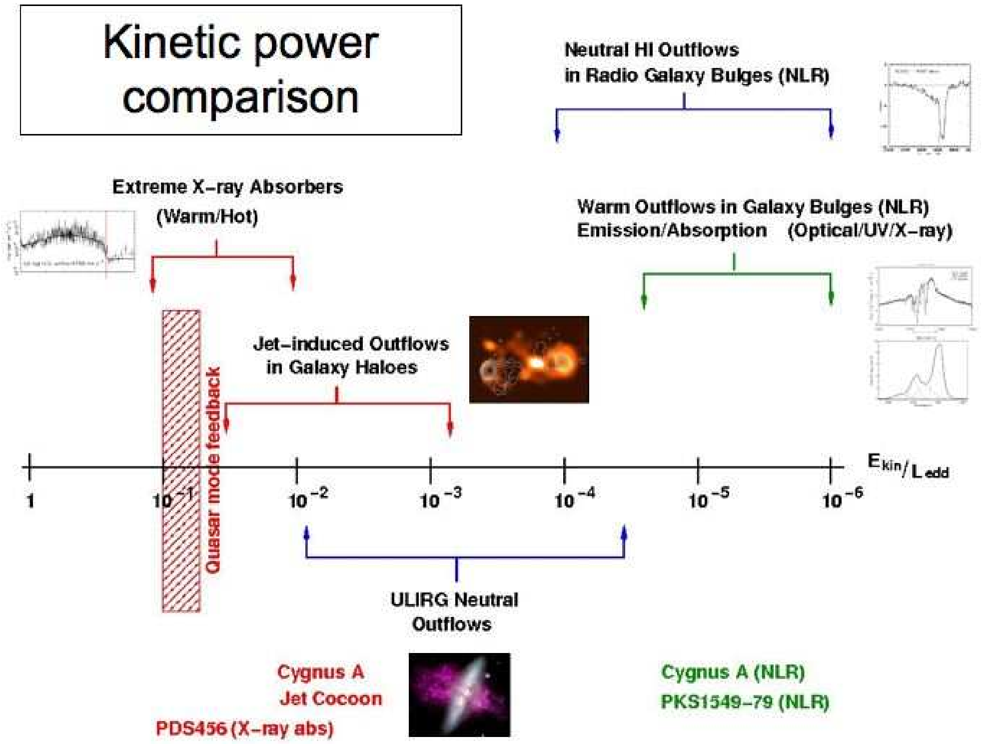

Fig. 4. The kinetic powers measured for the various types of AGN-induced outflows compared with those deduced for the neutral outflows in ULIRGs. The kinetic powers in the outflows have been normalised by the Eddington luminosities of the black holes in the galaxies concerned.

blueshifted wings to the HI 21cm absorption line feature detected against the radio cores of several nearby radio galaxies (Morganti et al. 2005a,b). Although the kinetic powers of the neutral outflows are not as large as those deduced for forementioned warm/hot X-ray outflows, they a both more massive and more energetic than the warm NLR outflows detected in narrow optical emission lines and UV/X-ray absorption features. Based on the detailed morphological association between the blueshifted HI features and the radio features (e.g. Morganti et al. 2005a), it appears likely that the neutral outflows are driven by the mechanical power of the radio jets, rather than the radiative power of the AGN. What remains surprising is that the absorbing clouds can cool to a neutral phase following acceleration to velocities up to thousands km s^{-1} by the jet-induced shocks.

5. Summary of outflow properties and comparison with starbursts

If the outflows associated with AGN represent the dominant form of feedback in the host galaxies, then we should expect the AGN-induced outflows to be at least as massive and energetic as those driven by supernovae in extreme starburst objects such as ULIRGs. In this context, the neutral outflows detected in ULIRGs using the optical NaID absorption doublet (Rupke et al. 2005a,b; Martin 2005) provide a useful fiducial. Figures 3 & 4 compare the mass outflow rates and kinetic powers of ULIRG neutral outflows with the various types of AGN-induced outflows discussed in this review. It is notable that only the large scale outflows driven by the radio jets, and the warm/hot outflows detected at X-ray wavelengths, are as powerful as the neutral outflows associated with ULIRGs; in general the warm NLR outflows are less massive and powerful, although the neutral outflows detected in some radio galaxies are comparable with the ULIRG outflows. This calls into question the general importance of the quasar mode feedback effect, at least in active galaxies in the local Universe.

6. Conclusions

Outflows have been detected on all scales in the host galaxies of AGN. On the scales of galaxy haloes and clusters it is now clear that the radio jets have a major effect on the energy balance/kinematics of the hot and warm ISM. However, the energetic significance of the quasar mode feedback effect associated with AGN-driven winds on the scale of galaxy bulges is much less certain. Further observations that probe the full range of gas phases are required in order to properly understand the impact of AGN-induced outflows on the evolution of the host galaxies.

Acknowledgements. I thank my collaborators Dave Axon, Dan Batcheldor, Joanna Holt & Raffaella Morganti for their contribution over the years.

References

Batcheldor, D., Tadhunter, C., Holt, J., Morganti, R., O'Dea, C.P., Axon, D.J., Koekemoer, A., 2007, ApJ, 661, 70

Benson, A.J., Bower, R.G., Frenk, C.S., Lacey, C.G., Baugh, C.M., Cole, S., 2003, ApJ, 599, 38

Best, P.N., Kaiser, C.R., Heckman, T.M., Kauffmann, G., 2006, MNRAS, 368, L67

Bower, R.G., Benson, A.J., Malbon, R., Helly, J.C., Frenk, C.S., Baugh, C.M., Cole, S., Lacey, C.G., 2006, MNRas, 370, 645

Clark, N.E., Axon, D.J., Tadhunter, C.N., Robinson, A., O'Brien, P.,1998, ApJ, 494, 546

Crenshaw, D.M., Kraemer, S.B., George, I.M., 2003, ARA&A, 2003

Croton, D.J., et al., 2006, MNRAS, 365, 11

di Matteo, T., Springel, V., Hernquist, L., 2005, Nat, 433, 604

Holt, J., Tadhunter, C., Morganti, R., Bellamy, M., Gonzlez Delgado, R. M., Tzioumis, A., Inskip, K. J., 2006, 370,1633

Marconi, A., Hunt, L.K., 2003, ApJ, 589, L21

Martin, C.L., 2005, ApJ, 621, 227

Morganti, R., Oosterloo, T.A., Tadhunter, C.N., van Moorsel, G., Emonts, B., 2005a, A&A, 439, 521

Morganti, R., Tadhunter, C., Oosterloo, T., 2005, A&ALett, 444,L9

McNamara, B.R., Nulsen, P.E.J., 2007, ARA&A, 45, 117

Nesvadaba, N.P.H., Lehnert, M.D., Eisenhauer, F., Gilbert, A., Tecza, M., Abuter, R., 2006, ApJ, 650, 693

Pounds, K.A., Reeves, J.N., King, A.R., Page, K.L., O'Brien, P.T., Turner, M.J.L., 2003, MNRAS, 345, 705

Reeves, J.N., O'Brien, P.T., Ward, M.J., 2003, ApJ, 593, L65

Reeves, J.N., Done, C., Pounds, K., Terashima, Y., Hayashida, K., Anabuki, N., Uchino, M., Turner, M., 2008, MNRAS, 385, L108

Rukpe, D.S., Veilleux, S., Sanders, D.B., 2005a, ApJ, 632, 751

Rupke, D.S., Veilleux, S., Sanders, D.B., 2005b, ApJS, 160, 115

Solórzano-Iñarrea, C., Tadhunter, C., Axon, D., 2001, MNRAS, 323, 965

Tadhunter, C., Wills, K., Morganti, R., Oosterloo, T., Dickson, R., 2001, MNRAS, 327, 227

Tadhunter, C., Marconi, A., Axon, D., Wills, K., Robinson, T.G., Jackson, N., 2003, MNRAS, 342, 861

Taylor, M.D., Tadhunter, C.N., Robinson, T.G., 2003, MNRAS, 342, 995

Tremaine, S., et al., 2002, ApJ, 574, 740

Veilleux, S., Cecil, G., Bland-Hawthron, J., 2005, ARA&A, 43, 769

Villar-Martin, M., Tadhunter, C.N., Morganti, R., Axon, D.J., Koekemoer,A., 1999, MNRAS, 307, 24

Wilson, A.S., Smith, D.A., Young, A.J., 2006, ApJ, 644, L9