Nuclear Activity in Galaxies Across Cosmic Time
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Tracing AGN feedback, from the SMBH horizon up to cluster scales

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Abstract. Observations performed in the last decades have shown that supermassive black holes (SMBHs) and cosmic structures are not separate elements of the Universe. While galaxies extend on spatial scales about ten orders of magnitude larger than the horizon of SMBHs, black holes would not exist without matter feeding them, and cosmic structures would not be the same without feedback from SMBHs. Powerful winds/jets in active galactic nuclei (AGN) may be the basis of this co-evolution. Synergistic observations in the X-rays and other wavebands have been proven to be fundamental to map AGN winds from the event horizon up to galaxy scales, providing a promising avenue to study the multi-phase SMBH feeding and feedback processes. Moreover, a spatially resolved, spectroscopic analysis of AGN in clusters will allow us to probe the multiphase medium ranging from galactic up to cluster scales. Revolutionary advances are expected in the upcoming decade with new multi-wavelength observatories, ranging from radio to X-rays.

Keywords. Active galactic nuclei, supermassive black holes, AGN feedback, X-ray astronomy, AGN winds

1. Introduction

Several observational and theoretical inferences require the existence of fundamental connections between the activity of supermassive black holes (SMBHs) and their host galaxies. For instance, the $M-\sigma$ relation indicates that the larger the SMBH mass, the larger is the velocity dispersion of stars in the bulges of galaxies (e.g., Kormendy & Ho 2013; Shankar *et al.* 2019). Moreover, active galactic nuclei (AGN) feedback is theoretically required in order to quench star formation in the most massive galaxies and to adequately model the observed distribution (e.g. Bower *et al.* 2012). How SMBHs, which gravitationally dominate on a linear size more than a billion times smaller than a galaxy and with a mass only about 0.1% of the stellar bulge mass (e.g., Magorrian *et al.* 1998; Häring & Rix 2004), can affect the galaxy scale environment is still debated.

Nevertheless, it is important to note that the gravitational energy of SMBHs far exceeds the binding energy of an entire galaxy bugle, thus even if a small fraction of such energy is converted and deposited in the galaxy environment, it could have a significant influence (e.g., Hopkins & Elvis 2010). Indeed, AGN radiation, jets or winds can release a significant amount of mass and energy in the host galaxy environment (e.g., Fabian 2012). However, it still remains to quantify the intensity the SMBH feedback on galaxy evolution and to establish the dominant mechanisms.

Accretion disk winds, and in particular ultra-fast outflows (UFOs), may play an important role in AGN feedback. Such UFOs are primarily observed as mildly-relativistic

($v_{out} \simeq 0.1$c) and highly ionized absorbers in the X-ray spectra of $>30\%$ of local radio-quiet and radio-loud AGN (e.g. Tombesi *et al.* 2010, 2011, 2014; Gofford *et al.* 2013). Although with relatively large uncertainties, their mass outflow rates and energetics are found to be comparable to the AGN accretion rate and higher than a few percent of the AGN luminosity, respectively (e.g., Tombesi *et al.* 2012, 2013; Gofford *et al.* 2015).

2. Overview

2.1. *From nuclear to galaxy scale feedback*

In order to effectively impact the host galaxies, AGN winds need to propagate from the accretion disk and to entrain/disrupt the host interstellar medium up to galaxy scales. In our Tombesi *et al.* (2015) work we reported, for the first time observationally, a link between the nuclear, mildly relativistic UFO observed in the X-rays with *Suzaku* and the galaxy-scale molecular outflow in the IR detected with *Herschel* in the ultra-luminous infrared galaxy (ULIRG) IRAS F11119+3257. The OH region of the IR spectrum of the galaxy shows a prominent P-Cygni line profile indicating a molecular outflow with a maximum velocity of $\simeq 1{,}000$ km s^{-1}, implying a mass outflow rate of ~ 800 $M_{\odot}$/yr and a distance of >300 pc from the center Veilleux *et al.* (2013). Such massive molecular outflows, potentially affecting star formation in the host, were detected in several other sources, but their connection with the AGN was unclear (e.g., Sturm *et al.* 2011). The X-ray detection of a highly ionized and massive UFO with velocity of $v_{out} \simeq 0.25$c provided the evidence relating the phenomenon to AGN feedback (Tombesi *et al.* 2015).

The presence and characteristics of the X-ray UFO and the molecular outflow were subsequently independently confirmed using data from *NuSTAR* and *ALMA* in the mm-band, respectively (Tombesi *et al.* 2017; Veilleux *et al.* 2017). The energetics of the X-ray UFO and the molecular outflows in IRAS F11119+3257 support theoretical models describing the origin of galaxy-scale molecular outflows as due to a energy-conserving hot bubble inflated by the inner AGN wind, with a coupling efficiency of $\sim 20\%$ (e.g., Faucher-Giguère & Quataert 2012; Zubovas & King 2014).

Recent results on other sources support such picture, but the coupling between the inner UFO and the neutral/molecular outflow is found between the two extreme regimes of momentum- and energy-driving, indicating either a low efficiency of the coupling and/or in-situ formation of molecular gas depending on the particular environment in each galaxy (Feruglio *et al.* 2015, 2017; Mizumoto *et al.* 2019; Bischetti *et al.* 2019. In Fig. 1 we show the recent results on another ULIRG, IRAS F05189−2524, along with a collection of literature results (Smith *et al.* 2019).

Observational evidence for the physical interaction between the putative X-ray UFO and the shocked ISM was hard to obtain. However, an intersting result was found by our group while studying the X-ray spectrum of the quasar PG 1114+445 (Serafinelli *et al.* 2019). This source was observed 12 times with *XMM-Newton* and once by *ASCA*. We found three distinct X-ray absorbers, variable but persistent over 15 years. The average parameters of the absorbers over the whole X-ray monitoring are: Abs1 with $\log N_H = 21.88 \pm 0.05$ cm^{-2}, $\log\xi = 0.35 \pm 0.04$ erg s^{-1} cm, and $v_{out} \simeq 530$ km s^{-1}; Abs2 with $\log N_H = 21.5 \pm 0.2$ cm^{-2}, $\log\xi = 0.50 \pm 0.36$ erg s^{-1} cm, and $v_{out} = 0.120 \pm 0.029$ c; Abs3 with $\log N_H = 22.9 \pm 0.3$ cm^{-2}, $\log\xi = 4.04 \pm 0.29$ erg s^{-1} cm, and $v_{out} = 0.145 \pm 0.035$ c.

The first absorber is consistent with the typical parameters observed for X-ray warm absorbers (WAs) and it has a counterpart observed in the UV (Mathur et al. 1998). The third absorber is consistent with the typical highly ionized and mildly relativistic UFOs observed in Seyfert galaxies (e.g., Tombesi *et al.* 2011). Instead, the second absorber seems to have parameters which are intermediate between the two, with column and ionization

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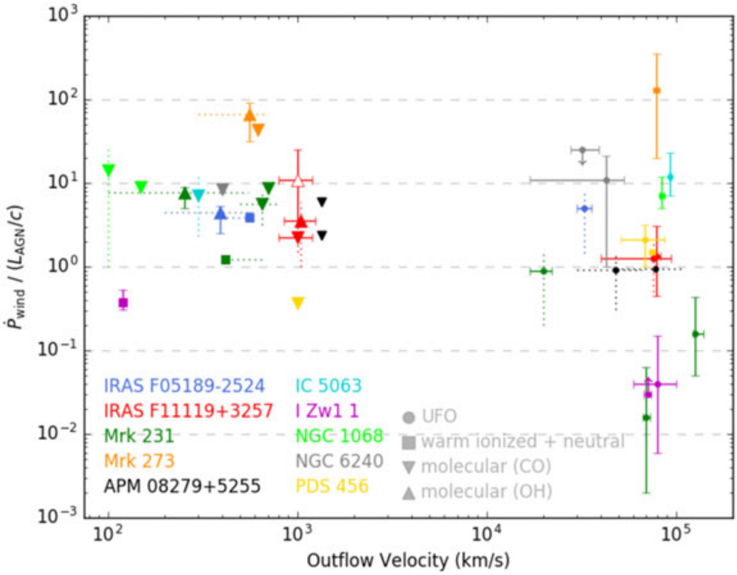

Figure 1. The momentum rate ($\dot{P}_{wind}$) normalized by the momentum of the radiation (L_{AGN}/c) is plotted against the wind outflow velocity for ten objects with observed UFOs and large-scale galactic outflows with good constraints on their spatial scales. Solid error bars indicate that upper and lower errors were calculated whereas dotted error bars indicate that only a range of values was provided. Arrows indicate limits. UFO measurements are plotted as circles, warm ionized and neutral gas as squares, the molecular (CO) as downward triangles, and the molecular (OH) as upward triangles. For molecular measurements, filled symbols indicate a time-averaged momentum rate whereas an open symbol is an "instantaneous" or local momentum rate. Figure adapted from Smith *et al.* (2019).

of WAs and velocity of UFOs. We interpret this intermediate absorber as an "Entrained ultra-fast outflow" (E-UFO) indicating the interaction region between the nuclear UFO and the ambient medium in this galaxy at a distance of ~100 pc from the central AGN. The shock or interaction region is likely clumpy and unstable due to Rayleigh-Taylor and Kelvin-Helmholtz instabilities. Absorbers with similar characteristics to the E-UFO discussed in Serafinelli *et al.* (2019) and complex multi-phase Fe K outflows are being found in an incresing number of sourcers (e.g., Gupta *et al.* 2013, 2015; Longinotti *et al.* 2015; Pounds *et al.* 2016; Reeves *et al.* 2016; Middei *et al.* 2020).

2.2. *From nuclear to cluster scales feedback*

It is widely known that AGN in galaxy clusters preferentially reside in the central brightest cluster galaxy (BCG) and can even influence the cluster gas through powerful winds or jets (e.g., Fabian 2012). However, it is still hard to observationally constrain and quantify such effect.

In Tümer *et al.* (2019) we recently reported a detailed X-ray spectral/imaging analysis of *XMM-Newton* and *Chandra* observations of the non-cool core (NCC) galaxy cluster MKW 08 and its central brightest cluster galaxy (BCG), namely NGC 5718. As shown in Fig. 2, we have been able to trace a multi-phase medium extending from within the interstellar medium/corona of the central BCG at scales of less than ~3 kpc with temperature of $kT \simeq 1$ keV, up to the hot intracluster medium (ICM) with temperature of $kT \simeq 4$ keV for scales larger than ~10 kpc up to ~500 kpc. The cooling time of the 1 keV gas at scales of less than 3 kpc is estimated to be of ~65 Myrs. This is much

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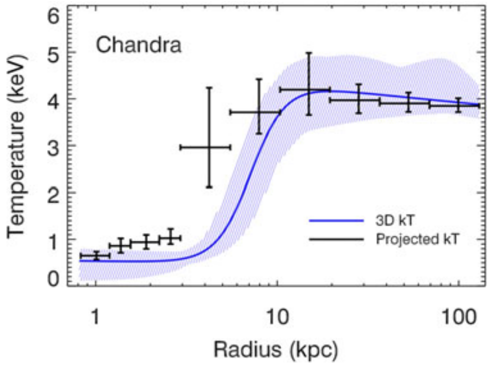

Figure 2. Projected radial ICM temperature values plotted over the deprojected temperature profiles using *Chandra* X-ray observations of the galaxy cluster MKW 08 centered on the BCG. Confidence contours (blue) were propagated from Monte Carlo realizations of the fit analytical functions. Figure adapted from Tümer *et al.* (2019).

shorter compared to the > Gyrs timescales for the ICM and it requires a heating source in order to counterbalance catastrophic cooling. We find that AGN feedback may provide the main source of heating.

3. Implications

Our recent observational results support the picture of a mutual evolution between SMBHs and their host galaxies. This is in accordance with recent theoretical works and simulations exploring the SMBH and galaxy environments from micro (sub-pc) to meso (kpc) and macro (Mpc) scales. The scenario that is emerging is one of a self-regulation of SMBH growth, with the feeding by chaotic cold accretion (CCA) raining down from the macro and meso environment mediated by the feedback from AGN winds and jets launched at micro scales (e.g., Gaspari & Sadowski 2017). Upcoming large multi-wavelength observatories in the next decade, from radio to X-rays, in synergy with the most advanced computer simulations, will provide unprecedented advances in this field of research.

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