Chapter 3:
Feedback on the host galaxy

https://doi.org/10.1017/S1743921323002818 Published online by Cambridge University Press

https://doi.org/10.1017/S1743921323002818 Published online by Cambridge University Press

Black Hole Winds at All Scales
Proceedings IAU Symposium No. 378, 2024
G. Bruni, M. Diaz Trigo, S. Laha & K. Fukumura, eds.
doi:10.1017/S1743921323002818

A Multiwavelength View of Black Holes and Outflows in Post-starburst Galaxies

Yuanze Luo

William H. Miller III Department of Physics and Astronomy
Johns Hopkins University, Baltimore, MD 21218, USA
email: yluo37@jhu.edu

Abstract. Post-starburst galaxies (PSBs) have quenched (significant decline in star formation rate) both recently and rapidly ($\lesssim$1 Gyr). They are thus promising in providing insights into activities that are happening at the early stage of quenching. While studies have suggested that black hole feedback in the form of active galactic nuclei (AGN) and outflows play important roles in quenching, the details of how they impact the host galaxies and their interplay with other quenching mechanisms are still not fully understood. We find that PSBs commonly show signatures of AGN activity but they appear to be weak and/or heavily obscured. These AGN might be able to drive outflows but they are likely not strong enough to remove gas from the host galaxy. Direct evidence of AGN quenching the star formation of the host galaxy is still missing and AGN likely quench by disturbing rather than expelling the gas.

Keywords. Galaxy evolution, Active Galactic Nuclei, Post-starburst galaxy, Quenching

1. Introduction

Observations of a large number of galaxies have revealed their color bimodality: many galaxies are either blue and star-forming, or red and quiescent (e.g., Baldry et al. 2004). The increase in the number density of quiescent galaxies from cosmic noon to the present day (e.g., Bell et al. 2012) suggests that galaxies evolve from blue to red as star formation (SF) is quenched and gas is consumed in stars or becomes unavailable for stellar synthesis.

Of the many quenching mechanisms, the role of AGN is a heated debate. While classical cosmological simulations predict powerful AGN-driven outflows (e.g., Hopkins et al. 2008) expelling gas from galaxies to quench SF, observational evidence of galaxy quenching from AGN feedback remains circumstantial (e.g., Smethurst et al. 2017; French et al. 2018). In particular, large molecular reservoirs found in quenched galaxies (e.g., Rowlands et al. 2015) suggest that gas is stabilized against collapse into stars, possibly by disturbance from weak outflows.

Deep Balmer absorption lines in the spectra of PSBs signal the excess of intermediate-age stars formed in a recent burst that was quickly quenched. PSBs represent the fast quenching track and are ideal laboratories for studying different activities at the onset of quenching. Here we summarize our findings from several studies on the AGN and outflow activity in PSBs.

2. From Case Study to a Larger Radio-detected Sample

IC 860 is a nearby ($z\sim$0.01) PSB for which we have exquisite multiwavelength from X-ray to radio wavelengths. It has a blue optical color and is at a very early stage of transitioning to the red sequence. The in-depth study was detailed in Luo et al. (2022). In short, IC 860 is found to harbor asymmetric spiral structures that could be the remnant

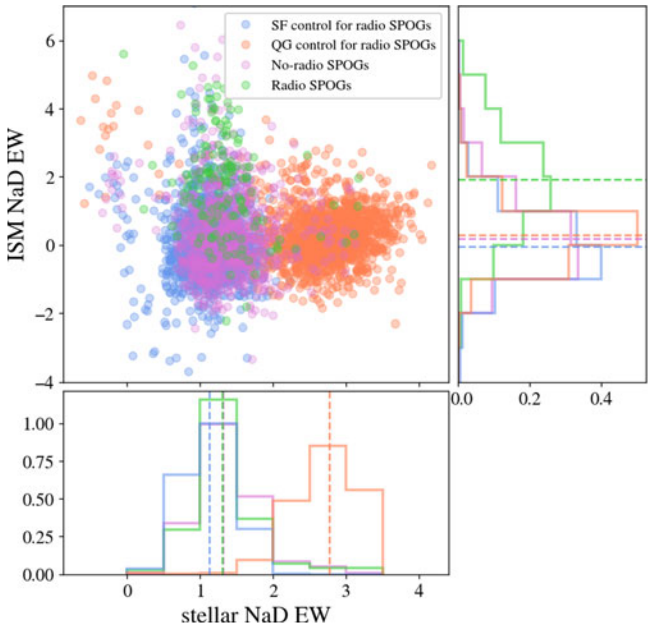

Figure 1. NaD absorption EW from ISM vs. from stellar absorption. The absorption from ISM traces cool neutral gas that could be SF fuel. Quiescent control galaxies show larger stellar NaD absorption EW as expected due to their older stellar population, while radio SPOGs show larger ISM NaD absorption EW. This fact could imply that radio SPOGs contain an elevated abundance of cool gas that is not actively forming stars, and processes associated with radio emission, e.g., AGN or small outflows, could be at play to quench SF.

of a recent merger, signatures of a weak AGN that is highly obscured, and a multiphase outflow in neutral and molecular gas that is unable to remove a significant amount of gas from the galaxy. The centrally concentrated CO molecular gas is compact (r $\sim$ 1 kpc) and kinematically misaligned with the stars. The molecular gas reservoir shows insufficient star formation efficiency, validating IC 860 as a quenching galaxy. The study implies that SF quenching and gas consumption have different timescales, and outflows prevent SF by disturbing rather than expelling the gas.

To search for AGN and outflows in a larger sample of PSBs, we turn to the Shocked POststarbust Galaxy Survey (SPOGS, Alatalo et al. 2016) which contains PSBs showing shock and/or AGN emission line ionization. Using radio emission as the smoking gun of AGN, we separate the SPOGs into radio-detected and non-radio-detected by comparing the sample to the Faint Images of the Radio Sky at Twenty Centimeters survey (FIRST, Becker et al. 1995). We also match in redshift and stellar mass to form control samples of SF and quiescent galaxies (QG). Following Luo et al. (2022), we use the NaD absorption feature at $\sim$5891 Å as a tracer of cold molecular gas and fit for its equivalent width (EW) utilizing spectra from the Sloan Digital Sky Survey (SDSS, Abazajian et al. 2009).

As shown in Fig 1, while QG show large stellar NaD EW due to old stellar populations as expected, radio-detected SPOGs show higher NaD EW from the interstellar medium (ISM) than other samples. This result suggests that there is an elevated abundance of cold gas in radio SPOGs, yet they are not actively forming stars. Processes associated with radio emission, e.g., AGN or small outflows, could be at play to quench SF. Outflows in the neutral gas, in particular, might be responsible for the larger EW we see in NaD absorption. We will look for more AGN/outflow evidence through MIR colors/spectral shape and comparison between observed radio emission and what is expected from SF.

https://doi.org/10.1017/S1743921323002818 Published online by Cambridge University Press

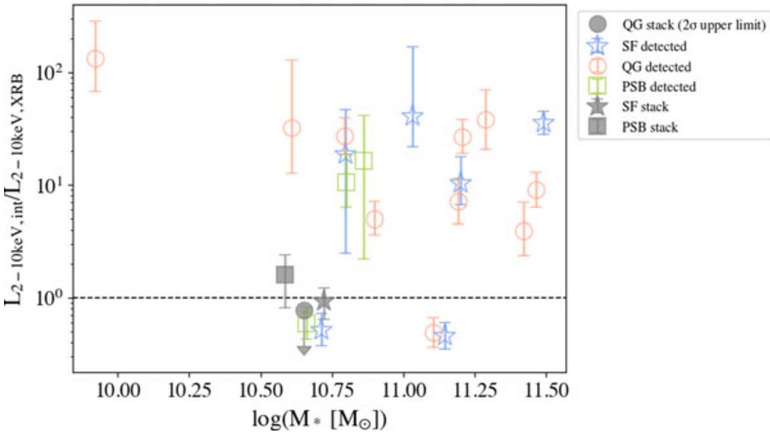

Figure 2. The ratio of the intrinsic X-ray luminosity and the expected X-ray luminosity from X-ray binaries plotted with stellar mass for both X-ray individually detected sources and the stacks of all non-detections. Individually detected PSBs show extra X-ray luminosity which could come from AGN. The stack of undetected PSBs shows a slightly enhanced ratio though still consistent with 1 considering the error bars. Given the limits of small samples, we will combine data at MIR, radio, and X-ray spectral information to constrain the AGN activity in PSBs.

This study has the potential to reveal the responsible mechanisms in galaxies at the early phase of quenching, and if outflows are confirmed, to provide a way of tracing outflows in transitioning galaxies with only radio data.

3. Exploring X-ray Observations via Stacking

While X-ray is another powerful window for probing highly energetic events like AGN, X-ray studies of PSBs have been scarce. High dust column density could greatly extinct the X-ray emission (like in IC 860), and the recent study by Lanz et al. (2022) on X-ray emission from SPOGs found that AGN, if present, have high obscuration and/or low luminosity.

X-ray sky surveys such as the eROSITA Final Equatorial Depth Survey (eFEDS, Brunner et al. 2022) allow us to perform stacking in search of faint sources that fall under the detection limit. We collected over 6000 spectral-selected PSBs from several current studies (Wild et al. 2007; Goto 2007; Pattarakijwanich et al. 2016; Alatalo et al. 2016; Tremonti et al. in prep) and 73 of them are covered by eFEDS observations. For these 73 PSBs, we match in redshift and stellar mass to control samples of SF and quiescent galaxies. We compare our samples to the detected source catalog in Brunner et al. (2022) and obtain their intrinsic luminosity estimation from X-ray spectral analysis in Liu et al. (2022). For all undetected sources, we create X-ray image cutouts and stack them following Toba et al. (2022). All luminosity measurements are converted into luminosity in the restframe 2–10 keV energy range, and we plot the ratio of the intrinsic luminosity of our galaxies to the estimated contribution from X-ray binaries (XRB, following Ito et al. 2022) in Fig 2.

X-ray-detected galaxies in different samples show some overlap in the $L_{X,int}/L_{X,XRB}$ vs. stellar mass parameter space, however, some PSBs do show extra X-ray luminosity that can not be explained by current SF. For stacked measurements, both SF galaxies and PSBs have $> 2\sigma$ detections. While both the SF and PSB stacks are consistent with $L_{X,int}/L_{X,XRB} = 1$, the PSB stack shows a slightly enhanced ratio. We note that $L_{X,XRB}$

https://doi.org/10.1017/S1743921323002818 Published online by Cambridge University Press

for PSBs is likely an overestimation given that the SF rates for PSBs are often overestimated (the various indicators tend to catch the "burst" part of the SF history). Although intrinsic extinction for detected sources is corrected for in Liu et al. (2022), we still need to estimate the intrinsic column density and correct for its effect on measured luminosity in the stacks. Taking into account these factors, the plotted $L_{X,obs}/L_{X,XRB}$ here for the PSB stack is a lower limit and is likely to exceed 1 after all corrections. Expanding this stacking analysis to the full eROSITA data which covers the entire sky when available is promising in reducing the error bars and better constraining $L_{X,obs}/L_{X,XRB}$ for the stacked measurements. The excess X-ray flux in PSBs over that expected from XRBs hints at hidden weak and/or obscured AGN in low-redshift PSBs. Our samples also have radio and mid-infrared data coverage and we will combine multiwavelength data to further investigate the existence and strength of AGN in PSBs.

4. Conclusions

To trace outflows and AGN in local (z <0.2) PSBs that have recently quenched or are still quenching their SF, we expand our case study to larger samples characterized by radio detection and X-ray coverage. We found an elevated abundance of neutral gas that is not forming stars and possible neutral outflows in a radio-detected PSB sample. X-ray stacking analysis reveals possible weak AGN lurking in nearby PSBs.

Our results suggest that AGN likely play a role in the quenching of local galaxies, but whether they are the driving factor of quenching or merely collateral events as quenching happens is still not clear. While AGN are found ubiquitously in quenched galaxies at higher redshifts (e.g., Ito et al. 2022), evidence for AGN in local galaxies at the early stage of quenching remains weak or tentative. Low-redshift galaxies appear able to maintain their molecular gas reservoir with a low SF rate for several Gyr until they finally become red and gas-depleted. The power of multiwavelength data is crucial in characterizing AGN activity level in local PSBs and for testing models (e.g., Hopkins et al. 2008) predicting that the AGN phase lasts a few hundred Myr after the starburst ends to help expel remaining gas as the galaxy becomes quiescent. We have found that star formation ends not with a bang but a whimper in the local universe, and more investigation is underway to confirm this result in larger samples.

References

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543
Alatalo, K., Cales, S. L., Rich, J. A., et al. 2016, ApJS, 224, 38
Baldry, I. K., Glazebrook, K., Brinkmann, J., et al. 2004, ApJ, 600, 681
Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
Bell, E. F., van der Wel, A., Papovich, C., et al. 2012, ApJ, 753, 167
Brunner, H., Liu, T., Lamer, G., et al. 2022, A & A, 661, A1
French, K. D., Yang, Y., Zabludoff, A. I., & Tremonti, C. A. 2018, ApJ, 862, 2
Goto, T. 2007, MNRAS, 381, 187
Hopkins, P. F., Cox, T. J., Kereš, D., & Hernquist, L. 2008, ApJS, 175, 390
Ito, K., Tanaka, M., Miyaji, T., et al. 2022, ApJ, 929, 53
Lanz, L., Stepanoff, S., Hickox, R. C., et al. 2022, ApJ, 935, 29
Liu, T., Buchner, J., Nandra, K., et al. 2022, A & A, 661, A5
Luo, Y., Rowlands, K., Alatalo, K., et al. 2022, The Astrophysical Journal, 938, 63, aDS Bibcode: 2022ApJ...938...63L
Pattarakijwanich, P., Strauss, M. A., Ho, S., & Ross, N. P. 2016, ApJ, 833, 19
Rowlands, K., Wild, V., Nesvadba, N., et al. 2015, MNRAS, 448, 258
Smethurst, R. J., Lintott, C. J., Bamford, S. P., et al. 2017, MNRAS, 469, 3670
Toba, Y., Liu, T., Urrutia, T., et al. 2022, A & A, 661, A15
Wild, V., Kauffmann, G., Heckman, T., et al. 2007, MNRAS, 381, 543