

Star-formation in active galaxies to $z \sim 2$: a perspective from Herschel studies

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In the era of deep, large-area far-infrared (FIR) surveys from the Herschel Space Telescope, the bulk of the star-formation in distant galaxies, once hidden by dust, is now being revealed. The FIR provides probably the cleanest view of SF in the host galaxies of Active Galactic Nuclei (AGNs) over cosmic time. We report results from studies of the relationships between SF, AGN activity and AGN obscuration out to $z = 2.5$, which employ some of the deepest Herschel and X-ray datasets currently available, while spanning orders of magnitude in the dynamic range of AGN properties. We highlight the role of gaseous supply in modulating both SF and AGN activity without necessarily implying a direct causal connection between these phenomenon. The role of starburst- or major merger-fueled AGN activity at low and high redshifts is discussed in the context of our results.

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An understanding of the interplay between the growth of galaxies and the growth of their central supermassive black holes (SMBHs) is now a fundamental element of galaxy evolution studies. This is due to the remarkable capability of SMBHs to alter the nature of the gaseous component of their host galaxies through the feedback of accretion power, and thereby regulate the formation of stars. AGN feedback is now considered a crucial ingredient in modern models of galaxy evolution [2, 4, 25, 27, 6], in particular as a pathway for the quenching of star-formation in massive galaxies and the maintenance of hot gaseous halos at temperatures $> 10^7$ K for timescales approaching the Hubble time [13].

Most of the local mass density in SMBHs was accreted near the peak of the luminous QSO era at $z \sim 2$. Therefore, a proper treatment of the origin and evolution of local SMBH scaling relationships [12, 28, 7] needs an understanding of the relationships between star-formation (SF) and AGN activity at that critical epoch, at which the star-formation rate (SFR) density of the Universe also peaked and when most of the current stellar mass was produced from gaseous raw material [3]. Such relationships are predicted by most models of ‘causal’ galaxy-SMBH co-evolution, i.e. models that require a direct physical link between the processes that govern SF and those that govern AGN activity. In particular, an element of synchronisation is key to such models: the SMBH has to grow substantially during a phase in which the galaxy also builds its stellar mass, or maintain a fixed temporal relationship to this phase. Any lack of synchronisation will smear out any causal co-evolutionary processes and undermine the development of tight scaling relationships. This may be contrasted to developing concepts that suggest that the simple hierarchical assembly of SMBHs and galaxies is sufficient for determining SMBH scaling laws [8]. In such models, causal co-evolution is not required.

Towards a more constrained observational view, we have undertaken one of the largest current studies of the relationship between SF and nuclear activity, spanning local redshifts to $z = 2.5$ over 4 orders of magnitude in AGN luminosity. The study builds on the best current X-ray surveys for the identification of AGN in well-studied extragalactic multi-wavelength fields. SF is probed through the use of far-infrared (FIR) photometry from the Herschel Space Observatory, building on its unprecedented collecting area – the largest astronomical mirror in space – and cryogenically-cooled instrumentation in the FIR. For the work reported here, we primarily rely on data from the Photodetector Array Camera and Spectrometer (PACS) instrument on Herschel, taken as part of the PACS Evolutionary Probe (PEP) GTO [11] and the GOODS-Herschel GO [5] programs. Our study employs 100 and 160 μm maps in the two GOODS fields (North and South) and the COSMOS field, with additional 70 μm data in GOODS-S. Using a combination of prior-based source extraction and stacking of non-detections, we derive mean fluxes of various subsamples of sources, typically binned in redshift and at least one other quantity such as X-ray luminosity (corrected for absorption in all cases) and X-ray obscuration. From these measurements, we interpolate rest-frame mean 60 μm luminosities (L_{60}). Several studies, including our own, have shown that wavelengths this far in the IR are very weakly affected by AGN-heated dust emission, even the stacks of IR-faint samples [17, 14, 20]. Measurements in these bands track the total IR luminosity and the galaxy-integrated dust-obscured SFR.

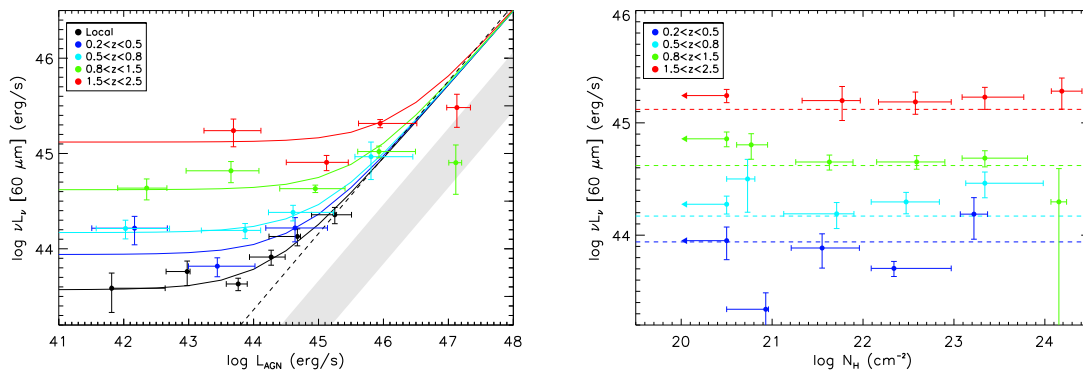


Figure 1: Left: Trends between the mean rest-frame 60 μm luminosity (L_{60}) and the bolometric luminosity of the AGN (L_{AGN}). Standard bolometric corrections are used to estimate L_{AGN} from the 2-10 keV X-ray luminosity. L_{60} is measured in given bins in redshift and L_{AGN} by stacking subsamples into PACS maps. In addition to the Herschel photometry, IRAS-based L_{60} estimates of the local sample of Swift/BAT AGNs are also included, from the compilation of [10] and [24]. The dashed line is from [18] and the shaded region shows the part of the diagram occupied by pure AGN SEDs. **Right:** Trends between the L_{60} and the nuclear obscuration of AGNs, expressed as an equivalent Hydrogen obscuring column (N_H). At all redshifts, only weak correlations are observed, driven more by covariances between L_{AGN} and N_H in X-ray datasets. See [20] for more details.

1. The Relationship between Star-Formation and AGN power

Figure 1 presents trends between L_{60} , a quantity that is roughly proportional to SFR, and the bolometric luminosity of AGNs (L_{AGN}). At low AGN luminosities, the mean SFR of X-ray selected AGNs is independent of L_{AGN} at all redshifts, but rises steadily with redshift in a manner that tracks the mean SFR of massive inactive galaxies [30]. At $z < 1$, following a characteristic turnover at $L_{AGN} > 10^{44-45} \text{ erg s}^{-1}$, a correlation is seen between L_{60} and AGN output at high nuclear luminosities. We interpret this turnover as the increased importance of starburst or merger-driven AGN fueling at these luminosities, since models of these mechanisms predict such a correlation [20]. At higher redshifts, the characteristic correlation weakens or disappears and a flat trend is seen across all AGN luminosities. While still to be securely confirmed, the lack of a strong trend suggests that, at higher redshifts, disk-instability mediated fueling of even rather luminous AGNs (i.e. fast growing black holes, [1]) may be more important at the expense of merger-driven fueling or other mechanisms that synchronize SF and AGN activity.

2. The Supply of Cold Gas modulates Low and Moderate AGN Activity

SF galaxies display a relatively tight relationship between SFR and stellar mass (M_*), popularly known as the SF Main Sequence [19, 30, 29]. After accounting for the effects of AGN contamination on host stellar mass estimates, [23] find that L_{60} in AGNs also tracks M_* in a similar fashion as inactive galaxies. However, a small enhancement of ≈ 0.2 dex is found in the mean SFR of AGNs over inactive galaxies, which is at apparent odds with the very similar distributions of SFRs found from FIR studies of star-forming galaxies and AGNs [15]. In [22], we studied the

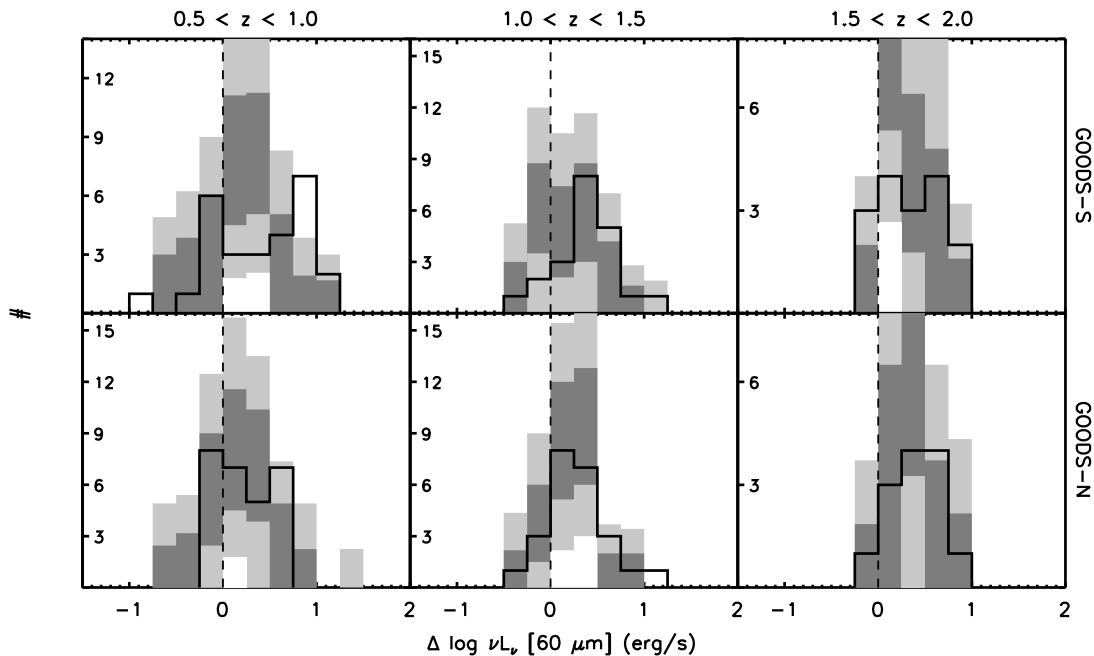


Figure 2: A comparison of the distribution of SFR offsets from the Main Sequence between AGNs (open histograms) and mass-matched inactive control galaxies (shaded histograms) in the two GOODS fields. The shadings in the latter histograms represent the scatter in the SFR distributions from 1000 bootstrap samples drawn from the inactive galaxy population: dark/light histograms are the $1/2\sigma$ scatter. The dashed line is the zero offset: the ridge line of the Main Sequence. The AGNs show SFR distributions that are statistically equivalent to inactive galaxies. See [22] for more details.

SFR distributions and PACS detection rates of AGNs and inactive galaxies, taking into account the unusual mass function of AGN hosts, which differs from the general inactive galaxy sample [9, 26, 21]. This was done using the deepest current FIR data available in any extragalactic field: the PEP+GOODS-Herschel combined maps. The SFR distributions of low-to-moderate luminosity AGNs are statistically indistinguishable from inactive galaxies in both fields and at all redshifts (Figure 2), confirming the results of [15]. However, the PACS detection rates of AGN hosts are always higher than equally massive inactive galaxies at $> 3\sigma$ significance, implying that AGNs are most likely to be in SF hosts than in passive hosts. In particular, we show that the high incidence of AGN in the ‘Green Valley’ is not a consequence of a link between AGN activity and the quenching of their hosts, but mostly driven by mass selection effects. AGN are in fact found less frequently in quenching or quiescent galaxies. We attribute this to the low supply of cold gas in such systems, since cold gas are required for both the fueling of radiatively efficient modes of AGN activity as well as current SF.

3. The Relationship between Star-Formation and AGN obscuration

A key prediction of some models of co-evolution is a close association between starburst activity in the host galaxy and obscured black hole growth. A search for trends between L_{60} and

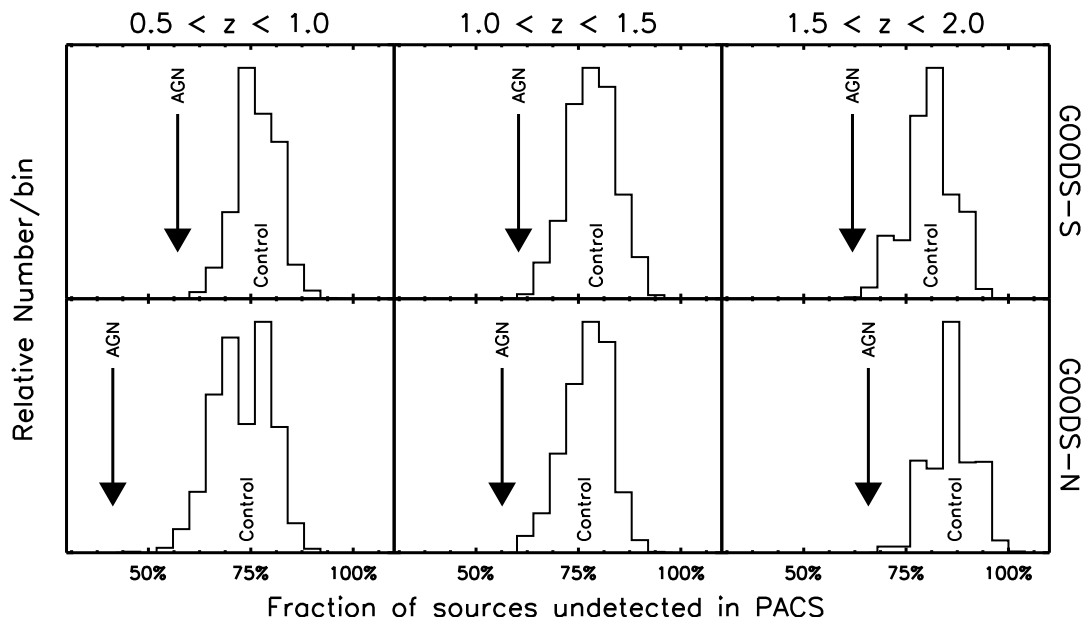


Figure 3: AGNs are more likely to be SF hosts than massive galaxies of the same stellar mass. Here we compare, for AGNs and mass-matched inactive control galaxies, the fractions of sources *not detected* in deep Herschel/PACS data. This fraction encompasses all quenching and quiescent galaxies in these samples. The histogram for the control sample comes from 1000 bootstrap samples drawn from the inactive galaxy population, which may be compared to the arrow which shows the fraction among X-ray AGNs. Typically 75-80% of massive galaxies lie below the PACS detection limit, while only 55-60% of AGN do so.

the X-ray obscuration towards the nucleus finds essentially no relationships between them out to $z \sim 2.5$ (Figure 1). Weak correlations visible in such a diagram are primarily driven by selection effects, since only the most luminous obscured AGNs are detectable in X-ray surveys.

4. Implications for the Co-evolution of Galaxies and Black Holes

Causal or synchronized models of the co-evolutionary connection of SMBHs and their host galaxies predict strong correlations between SF and AGN activity. Our studies show that these correlations are weak among low and moderate luminosity AGNs, suggesting that strong co-evolution does not occur in these systems. More importantly, we provide some evidence for the notion that synchronized growth is weak at high redshifts even among luminous AGNs. However, our study of low and moderate luminosity AGNs suggests an important, though indirect, channel for co-evolution. As a galaxy accretes gas from the cosmic web, some fraction of this gas stochastically and intermittently falls into the SMBH through normal secular inflow processes. SMBHs grow faster in galaxies with more cold gas, but it is precisely these galaxies that also have a higher mean SFR. SMBH scaling relations, and correlations between mean SMBH accretion rate and stellar mass [16], may be mediated more by the availability or supply of fuel rather than causal links between AGN fueling and star-formation.

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