DO MOST ACTIVE GALACTIC NUCLEI LIVE IN HIGH STAR FORMATION NUCLEAR CUSPS?

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ABSTRACT

We present early results of the Herschel PACS (70 and 160 \( \mu \)m) and SPIRE (250, 350, and 500 \( \mu \)m) survey of 313 low redshift (\( z < 0.05 \)), ultra-hard X-ray (14–195 keV) selected active galactic nuclei (AGNs) from the 58 month Swift/Burst Alert Telescope catalog. Selection of AGNs from ultra-hard X-rays avoids bias from obscuration, providing a complete sample of AGNs to study the connection between nuclear activity and star formation in host galaxies. With the high angular resolution of PACS, we find that >35% and >20% of the sources are “point-like” at 70 and 160 \( \mu \)m respectively and many more have their flux dominated by a point source located at the nucleus. The inferred star formation rates (SFRs) of 0.1–100 \( M_\odot \) yr\(^{-1} \) using the 70 and 160 \( \mu \)m flux densities as SFR indicators are consistent with those inferred from Spitzer Ne\( \alpha \) fluxes, but we find that 11.25 \( \mu \)m polycyclic aromatic hydrocarbon data give \( \sim 3 \times \) lower SFR. Using GALFIT to measure the size of the far-infrared emitting regions, we determined the SFR surface density (\( M_\odot \) yr\(^{-1} \) kpc\(^{-2} \)) for our sample, finding that a significant fraction of these sources exceed the threshold for star formation driven winds (0.1 \( M_\odot \) yr\(^{-1} \) kpc\(^{-2} \)).

Key words: galaxies: active – galaxies: nuclei – galaxies: Seyfert – infrared: galaxies – stars: formation

Online-only material: color figures

1. INTRODUCTION

Over the past 20 years there have been many indications of a strong connection between star formation and nuclear activity (e.g., Alexander et al. 2005; Schweitzer et al. 2006; Netzer et al. 2007; Netzer 2009; Diamond-Stanic & Rieke 2012; Rosario et al. 2012; Santini et al. 2012). However, much of this work is based on observations of moderate to high redshift optically or infrared (IR) selected systems in which it is difficult, because of a lack of angular resolution, to connect the IR radiation to star formation or active galactic nuclei (AGNs) processes. Optically selected samples are also strongly biased with respect to dust, AGN absorption, and other galaxy host properties (Mushotzky 2004).

Because the nuclear light from the AGNs frequently makes analysis of the stellar population difficult, many authors have focused on the analysis of type II AGNs and thus have had to assume that the connection between the AGNs and the host galaxy are similar in type IIs and IIIs. It is not clear that such an assumption is correct since recent results (Donoso et al. 2013) show that obscured sources have a higher clustering signal than unobscured sources and thus lie in more massive objects. Thus the nature of the host galaxies of type II AGNs are likely to be rather different from that of type Is.

Since, as we will show in this Letter, the IR radiation in low-z AGNs is strongly nuclear in nature, the assumption that commonly used star formation templates are sufficiently accurate to model the star formation in AGNs ignores the possibility that the AGNs may influence the spectral nature of the star formation (e.g., Meijerink et al. 2013). Many authors have made the strong assumption that the IR continuum originates solely from the torus (Nenkova et al. 2002; Fritz et al. 2006; Schartmann et al. 2008; Lira et al. 2013) to model the IR emission from the AGNs. Such assumptions can strongly affect the interpretation of the far-IR (FIR) radiation.

To understand the relation of star formation to AGN activity, the bolometric luminosity of the AGNs, and the nature of the IR continuum we have conducted a Herschel (Pilbratt et al. 2010) program of broadband (70–500 \( \mu \)m) imaging observations of 320 ultra-hard (14–195 keV) X-ray selected AGNs from the 58 month Swift Burst Alert Telescope (BAT) catalog (Tueller et al. 2010). Because of the essentially flux limited nature of this low redshift survey the luminosities of the objects are strongly correlated with redshift and span an ultra-hard X-ray luminosity range from 41.5 to 45.4 erg s\(^{-1} \). The vast majority of these objects are Seyfert galaxies, with very few LINERS or other extremely low luminosity AGNs or very high luminosity quasars.

The Swift BAT (Barthelmy et al. 2005) sample is selected entirely as a signal to noise limited catalog of sources detected in the 14–195 keV and identified with active galaxies via follow-up or archival observations. This sample is not biased with respect to the optical, IR, or radio properties of the host and has a very high identification fraction (Baumgartner et al. 2013). However, it is biased against so-called Compton thick AGNs in which the line of sight column density is greater than \( 2 \times 10^{23} \) cm\(^{-2} \). We have applied a low-redshift cutoff of \( z < 0.05 \) in order to obtain interesting constraints on the spatial origin of the FIR emission for the first time given Herschel’s angular resolution of 5′′ FWHM for its 70 \( \mu \)m waveband. Details of the sample selection and observations will be discussed in M. Meléndez et al. (2014, in preparation). We obtained a completeness fraction of 94% at 70 \( \mu \)m, 80% at 160 \( \mu \)m, 85% at 250 \( \mu \)m, 68% at 350 \( \mu \)m, and 46% at 500 \( \mu \)m with 5\( \sigma \) confidence giving 296 sources at 70 \( \mu \)m and 259 at 160 \( \mu \)m.

In this Letter we focus on the higher angular resolution PACS (Poglitsch et al. 2010) data at 70 \( \mu \)m and 160 \( \mu \)m and leave to further work detailed modeling of the broadband spectra and

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http://heasarc.nasa.gov/docs/swift/results/bs58mon/
correlations with other wavebands (M. Meléndez et al. 2014, in preparation).

2. OBSERVATIONAL DETAILS

The vast majority of the BAT AGNs presented in this work are from our Cycle 1 open-time program (OT1_rushotz_1, PI: R. Mushotzky) with a total of 291 sources. We included an additional 22 BAT sources from different programs publicly available from the Herschel Science Archive (see M. Meléndez et al. 2014, in preparation, for details), giving a total number of 313 sources in our sample. For the sources obtained through our OT1 program the PACS imaging for the blue 70 μm (60–85 μm) and red 160 μm (130–210 μm) band was obtained simultaneously in mini-scan mode along two scan map position angles at 70° and 110°. Each orientation angle has a medium scan speed of 20″ s⁻¹, two scan legs of 3′0 length with 4′0 scan leg separation, and a repetition factor of one. The total time per observation was 52 s.

For the PACS data reduction we used the Herschel Interactive Processing Environment (Ott 2010) version 8.0. The “Level 0” observations (raw data) were processed through the standard pipeline procedures. To correct for the bolometers’ drift (low-frequency noise), both thermal and non-thermal (un correlated noise), and to create the final maps we used the algorithm implemented in Scanamorphos (v19.0, Roussel 2013).

PACS fluxes are measured through aperture photometry. Circular apertures of varying radii were placed to measure the source flux and concentric annuli were used to estimate the background flux. For the more extended sources, we used elliptical apertures and annuli. The apertures are chosen by eye to contain all of the observed emission at each wavelength and the background annulus was set to encompass a clean, uncontaminated sky region close to the source. Finally, aperture corrections were applied to account for flux outside the source apertures.

3. RESULTS

3.1. Point Source Contribution

Visually, it is easy to see that for a large fraction of our sample, the majority of the 70 μm emission originates from a small point-like component. To estimate the contribution from a centrally located point source, we extracted fluxes from a small 6″ aperture for the PACS 70 μm images and a 12″ aperture for the 160 μm image. The sizes of the apertures are roughly the FWHMs of the point-spread functions (PSFs) in each waveband to minimize contribution from any extended component. These point source fluxes are then compared to the total FIR flux as determined by M. Meléndez et al. (2014, in preparation).

Figure 1 shows the distribution of point source contributions for both 70 and 160 μm. We find that 274/296 (92.5%) of the objects have a point source contribution greater than 50% of the total flux at 70 μm and 229/259 (88.4%) at 160 μm. The remaining sources are mainly large, extended very nearby galaxies.

3.2. FIR Sizes

Using GALFIT (Peng et al. 2002), we estimated the FIR size of our sources by modeling the FIR surface brightness with a two-dimensional (2D) Gaussian. Because the shape of the PACS PSF is dependent on the details of the observation (i.e., scan angles, scan speed, etc.) and mapmaking technique, we downloaded and reduced an observation of one of the calibration stars, α Tau (OBSID 1342240755 and 1342240756). α Tau was observed with the same scan speed and scan angles as our sample, and we used the same scripts and Scanamorphos version to reduce the data and create a map. α Tau was then cut out of the map and input into GALFIT as the instrument PSF to be convolved with the chosen model. Through visual inspection of the residual images, it seems that, for 105/296 sources at 70 μm (50/259 at 160 μm) only a point source component is necessary to fit the surface brightness. This was verified by a detailed analysis which determined an upper limit on the size for these sources. This size was obtained by iteratively increasing the FWHM parameter for the Gaussian model until we achieved a 3σ change in χ², determining the largest a source could physically be but still be unresolved for PACS.

For another 106 objects at 70 μm (128 at 160 μm), the sources are quasi-resolved and a 2D Gaussian model fits the images well. We utilize the best-fit FWHM as the radius for the source size. We also tested an exponential profile to these sources at 70 μm since this has been found to fit star-forming disks. Both the Gaussian and exponential profile are special cases of the more general S´ersic profile with each having specific values of the “compactness” parameter, n (n = 0.5 and n = 1, respectively). However, all three profiles have different “size” parameters that are related to each other: effective radius $r_e$ for the S´ersic, scale length $r_s$ for the exponential, and FWHM for the Gaussian. To fairly compare the sizes found by the exponential and Gaussian profiles, we scaled each to $r_e$ using the following relations:

$$r_e = 1.678r_s$$

(1)

$$r_e = 0.588 \text{FWHM}.$$  

(2)

The median ratio of $r_e$ determined from the exponential to the Gaussian is 0.76, meaning an exponential profile finds even smaller effective sizes for our sources and using a Gaussian
is likely a conservative model to measure the FIR size of our sources. For the rest of this Letter we use the sizes found with the Gaussian model.

The rest of the sources in the sample are clearly extended and either have non-Gaussian morphologies (e.g., spiral or clumpy structure) and are too well resolved to be fit by this simple model. For this subsample, we use the aperture radius implemented to measure the global flux as a reasonable estimate of the size of the source. These should be at worst conservative upper limits since apertures were chosen by eye to fully encompass the FIR emission of each source.

In Figure 2 we show the distribution of source sizes with upper limits representing the “point-like” objects. We find a range of upper limits on the source size from a median value of 3′.1 at 70 μm and 7′.7 at 160 μm or a median value of 2 kpc at 70 μm and 5 kpc at 160 μm. Thus for the vast majority of the hard X-ray selected AGNs the dominant FIR component is nuclear in nature which is the same as what has been found in (U)LIRGS in the mid-IR (Díaz-Santos et al. 2010).

One possible explanation for the compactness of our sources is low sensitivity to faint extended emission due to the short exposures. We tested this by comparing the radial profiles of six sources that have duplicate longer exposure (at least a factor of four longer) observations in the Herschel archive. These observations were reduced in the same manner as our sample and the same mapmaking routine was used to create the maps. Comparison of the radial profiles shows no significant extended emission being missed in our short exposures in 5/6 sources out to radii of 80″, the shortest length of our images. The one source with “extra” extended emission in the longer exposure

Figure 2. Distribution of measured sizes and example sources for the point source sample (top), sample measured with GALFIT (middle), and sample with sizes equal to the aperture size (bottom). Each histogram contains two distributions, one for 70 μm (solid black) and one for 160 μm (dashed red). Each image is displayed with asinh scaling from a flux level of 0 to the maximum flux of the source. The black circles/ellipses outline the measured size used for the source. From to bottom the specific AGNs are Mrk 704, ESO 197-G04, and NGC 5674.

(A color version of this figure is available in the online journal.)
image, NGC 7465, seems to show a tidal tail due to interaction with a nearby companion, and is not related to star formation within the galaxy. We conclude that our short observations are not missing significant faint extended emission.

3.3. Star Formation Rates

To estimate the star formation rate (SFR) of our sources, we first used the monochromatic calibration of 70 and 160 μm from Calzetti et al. (2010). We compared these SFRs to those measured by the near IR Ne II (108 galaxies) and polycyclic aromatic hydrocarbon (PAH) 11.25 μm (79 galaxies) emission extracted from Spitzer Infrared Spectrograph spectra as well as 1.4 GHz radio fluxes (189 galaxies) from the NVSS catalog.

For the [Ne II] flux we performed a line fit with a polynomial to fit the continuum and a Gaussian for the line profile (Weaver et al. 2010). The 11.25 μm PAH feature was measured by integrating the flux above a spline-interpolated continuum (see Spoon et al. 2007 for details on the procedure). [Ne II] SFRs were calculated from the calibration in Meléndez et al. (2008) corrected for a Kroupa (2001) initial mass function while for the PAH 11.25 μm SFR we used the calibration from Diamond-Stanic & Rieke (2012). For 1.4 GHz we used the Murphy et al. (2011) calibration. We find (Figure 3) that the FIR inferred SFRs of 0.1–100 M⊙ yr⁻¹ are consistent with those inferred from Spitzer Ne II fluxes but with wide scatter, while the PAH 11.25 μm derived SFR are systematically 3× lower and the 1.4 GHz relation gives systematically higher SFRs by a factor of two to four. The discrepancy between the radio derived and FIR derived SFRs might be explained due to the presence of AGN-related emission in the radio, but the discrepancy in the PAH derived SFRs seem to suggest that PAHs are being destroyed by the AGNs or there is an error in either the Ne II or PAH calibrations.

The 70 μm SFRs are roughly a factor of two greater than the 160 μm rates if we use the Calzetti et al. (2010) calibration derived for starburst galaxies. If we renormalize the two rates, such that they both give the same SFR, the variance between the two estimators is still a factor of two. While all the SFR indicators are highly correlated, the wide range in inferred rates does not allow us to definitively assign all of the emission to star formation and thus the inferred rates may be significantly (factor of three) affected by AGN emission. This can also be seen in Figure 4 where a weak correlation between the AGN luminosity, inferred by the BAT luminosity (L_{AGN} ≈ 15L_{BAT}; Winter et al. 2012), and the 70 μm luminosity, which is being used as a tracer for star formation, is detected, especially for the Seyfert 1’s in our sample.

3.4. Star Formation Surface Density

Since we do not have Spitzer Ne II or PAH data for all of our sample we have used the 70 and 160 μm data to infer the
Figure 5. Comparison between the SFR surface density from the 70 μm calibration and the 160 μm calibration. Arrows correspond to lower limits on the SFR surface density. Black dashed lines are drawn at 0.1 M_☉ yr⁻¹ kpc⁻², the threshold for star formation driven winds from Heckman (2001). The solid lines represent the uncertainty of 0.3 (70 μm) and 0.5 (160 μm) dex in the star formation calibrations from Calzetti et al. (2010).

(A color version of this figure is available in the online journal.)

SFR surface density. Using these SFRs and estimates of the source size, we calculate an SFR surface density (M_☉ kpc⁻²) for both the 70 and 160 μm data (Figure 5). At least 30% and as many as 50% of the objects using 70 μm as the SFR indicator or between 20%–30% using 160 μm as the indicator have SFR densities larger than the empirical threshold of 0.1 M_☉ yr⁻¹ kpc⁻² needed to drive a wind (Heckman 2001). There is a very similar distribution in SFRs for objects that are resolved, partially resolved, or unresolved suggesting that the Herschel angular resolution is adequate for identifying nearby objects with high specific SFRs. The high rate of star formation surface density (M_☉ yr⁻¹ kpc⁻²) indicates that AGNs very often lie in nuclear starbursts which should drive winds. To our knowledge this is the first indication that Seyfert galaxies should have, frequently, star formation driven nuclear winds.

4. DISCUSSION

The general agreement, with large scatter, of the inferred SFRs using five different indicators shows that the assumption that the bulk of the 70 and 160 μm luminosities from our sources is consistent with star formation is reasonable. This discovery has only been made possible by the combination of an AGN sample unbiased with respect to host galaxy properties and the Herschel sensitivity and imaging capabilities. This concentration is seen in both type Is and IIs which show little or no color differences in the PACS data (M. Méndez et al. 2014, in preparation).

We are thus led to the conclusion that either a significant fraction of the hosts of low-redshift AGNs have nuclear starbursts, that a significant fraction of the 70 and 160 μm luminosity is not produced by star formation, or that the normalization of the various indicators of star formation is very different in the nuclear star-forming regions of AGNs. A similar conclusion was reached by Diamond-Stanic et al. (2012) and LaMassa et al. (2013) using Spitzer observations over a range of redshifts and inferring sizes and was predicted theoretically by Ballantyne (2008). However, this is the first time, to our knowledge, that this result is based on direct imaging of the star formation process and on an AGN sample which has direct measures of the AGN luminosity and is relatively unaffected by selection effects.

The strongly compact morphology of the low redshift BAT sample is a surprise, given their modest inferred SFRs, and indicates that even at moderate AGN luminosities the IR radiation is strongly nuclear in nature and thus might be connected to the AGN phenomenon. In a comparison with the KINGFISH sample (Kennicutt et al. 2011) of normal star-forming galaxies with Herschel PACS observations and similar optical absolute magnitudes (M_,opt < −19) and SFRs, the FIR surface areas, inferred from the apertures used for the global fluxes, are a factor of six larger than the FIR sizes of our sample. Comparison of the FIR to hard X-ray luminosities of X-ray selected AGNs (Rosario et al. 2012; Mulaney et al. 2012) show that the ratio L_IR/L_X increases considerably with redshift. If these high-z objects have the same morphology as our lower redshift sample, which will require ALMA to test, the strong relationship between SFR surface density and outflow velocity (Newman et al. 2012) would imply that virtually all of the high-z AGNs would have starburst driven winds.

5. CONCLUSIONS

The analysis of the 70 and 160 μm images of a sample of 313 nearby (z < 0.05) hard X-ray selected AGNs shows that in over 90% of the sources the bulk of the FIR radiation is point-like at the spatial resolution of Herschel (a median value of 2 kpc FWHM). The inferred SFRs from a variety of indicators (Ne ii, 70, 160 μm, PAH, and radio emission) agree within a scatter of 4 and are consistent with the idea that at least 30% of the FIR radiation is due to star formation. If the FIR is tracing nuclear star formation, then this is also tracing the cold molecular gas that could be fueling the AGNs as suggested by Hopkins et al. (2013). The combination of the SFRs and the upper limits on source size shows that at least 30% and as much as 50% of the sources have a SFR surface density above 0.1 M_☉ yr⁻¹ kpc⁻² which has been shown to be a threshold for SFR winds (Heckman 2001). It thus seems as if a large fraction of AGNs and perhaps virtually all have nuclear starbursts capable of driving winds.

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