CHANDRA/HERSCHEL SURVEY: THE BLACK HOLE ACCRETION/STARBURST CONNECTION

Abstract: We propose to analyse all the archival Chandra data in the Herschel Multi-tiered Extragalactic Survey (HerMES) to compile the largest sample ($N \sim 1600$) of powerful AGN at the main epoch of black hole growth, z=1-3, and to resolve current discrepancies on the star-formation rate of these systems. The combination of X-ray data with far-IR/submm observations provides the most robust constraints on the star-formation of AGN to test competing models for the interplay between galaxy formation and black hole growth. HerMES is ideally suited to studying star formation over the z=1-3 epoch and by adding Chandra data is the only region with the required X-ray/UV/optical/IR/submm coverage to do such a study.

1. AGN-Galaxy Co-evolution: There is now strong evidence that powerful active galactic nuclei (AGN) played a key role in the evolution of galaxies. The correlation of central black hole and stellar bulge mass (e.g. Magorrian et al 1998), and the similarity between the cosmic star formation history (e.g. Hopkins & Beacom 2006) and cosmic black hole mass assembly history (e.g. Aird et al 2010) both suggest that the growth of supermassive black holes (SMBH) is related to the growth of host galaxies. Understanding what drives the formation and evolution of galaxies and their central SMBHs remains one of the most significant challenges in extragalactic astrophysics.

Most recent models (e.g. Di Matteo et al. 2005; Hopkins et al. 2005, Bower et al. 2006, Croton et al. 2006) propose AGN feedback as the underlying physical process that links the build-up of the stellar population of galaxies, the formation of supermassive black holes (SMBHs) and the growth of the large scale structure of the Universe. Recent observational constraints provide first-order confirmation of this theoretical picture (e.g. Lehmer et al. 2009).

However, the sequence in which galaxies build up their stellar and black hole mass and the relationship between the two components are, as yet, poorly understood. In some models (e.g. Di Matteo et al. 2005, Hopkins et al. 2006) the stellar population and the SMBHs form almost simultaneously and therefore predict a correlation between star-formation and AGN activity. Alternatively the stellar population of galaxies may be accumulated first, followed by the main epoch of SMBH growth (e.g. Archibald et al. 2002, Cen 2011), so that star-formation and AGN activity to be unrelated, or even negatively correlated.

2. The X-ray & Far-IR Synergy: A major drawback in assessing the level of star-formation in AGN, particularly at $z > 1$, the main epoch of galaxy and SMBH formation, is the difficulty in decomposing the stellar from the AGN emission. When they are accreting rapidly, AGN can dominate the radiation from stars over almost the entire electromagnetic spectrum. Two key energy ranges allow us to separate the accretion from star formation almost with little ambiguity: The X-ray band provides a clean window in which the radiation from luminous AGN ($L_X(2-10\mathrm{keV}) > 10^{44}\,\mathrm{erg\,s^{-1}}$), can be observed with minimal contamination from star formation, while star-formation galaxies (SFG) emit a large fraction of their energy in the far-infrared/submm band where the AGN contribution is minimal.

Combining X-ray data with longer far-IR/submm wavelengths can provide a handle on the issue of the star-formation properties of AGN hosts. Although some progress has been made by exploiting the submm from the ground (e.g. Page et al 2001), and the long wavelength channels of *Spitzer/MIPS* (e.g. Trichas et al 2009; 2010, Symeonidis et al. 2010), it is the launch of ESA's *Herschel Space Observatory* and its capability to make large sensitive surveys of star formation in the far-IR/submm, which offers the best prospects for significant advance in this area.

3. Recent HerMES Results: Recent observational results on the far-IR/sub-mm properties of QSO hosts are conflicting. Lutz et al. (2010) and Shao et al. (2010) argue that the star-formation rate is positively correlated with AGN activity for luminous QSOs only, $L_X(2-10\,\mathrm{keV}) > 10^{44}\,\mathrm{erg\,s^{-1}}$.

The HerMES team finds a rapid decrease of the 250 μm detection rate at QSO luminosities, $L_X(2-10\,\mathrm{keV}) > 10^{44}\,\mathrm{erg\,s^{-1}}$, indicating suppression (rather than enhancement) of the star formation at high accretion luminosities (see Fig. 1; Page & Trichas 2011, Trichas & Page 2011). There is no doubt that this confusing picture is due to the small number of luminous AGN in the present isolated survey areas. Figure 1 clearly suffers from poor statis-

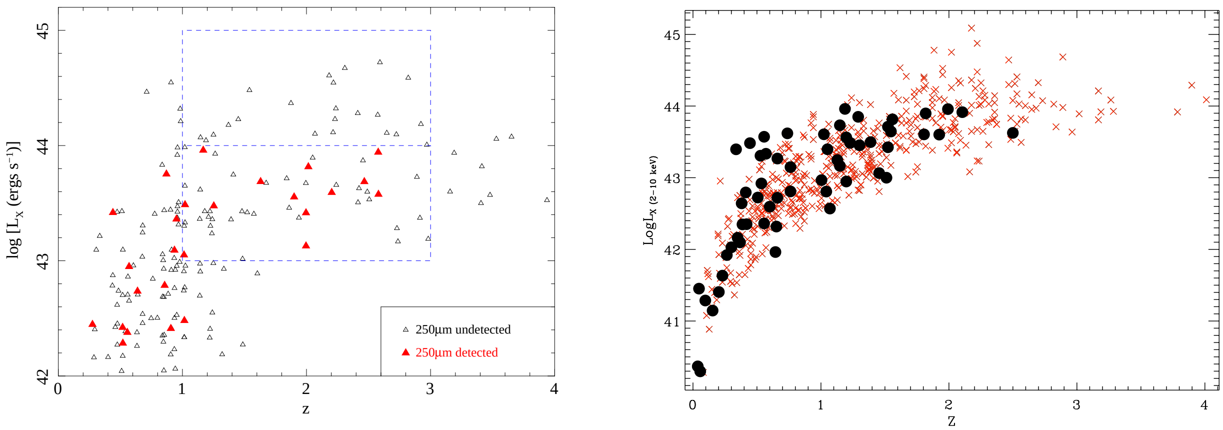

Figure 1: **Left** : The X-ray luminosity/redshift plane for sources from the *Chandra* 2 Ms observation of the HDFN. The red, filled triangles indicate the location of the X-ray sources with *Herschel*/250 μm detections (Page & Trichas, 2011). Note the complete absence of 250 μm detections above $\log(L_{2-10keV}/erg\,s^{-1}) > 44$ suggesting a lack of high SFRs among the most luminous X-ray sources. **Right** : The X-ray luminosity/redshift plane for sources from the *Chandra* 70ks observation of the Lockmnan Hole (Wilkes et al. 2009). The black, filled circles indicate the location of the X-ray sources with *Herschel*/250 μm detections (Trichas & Page, 2011). Similarly to the HDFN sources, there is complete absence of 250 μm detections above $\log(L_{2-10keV}/erg\,s^{-1}) > 44$.

tics, while Shao et al. (2010) find only 6 AGN in the CDF-N at redshifts $z \approx 1-3$ with $L_{2-10keV} > 10^{44}\,\mathrm{erg\,s^{-1}}$, too few for any meaningful constraints on the $L_{SFR} - L_{AGN}$ relation at bright luminosities.

However, the small number statistics problem is not because of lack of X-ray data, as there is substantial overlap between Chandra and Herschel fields (Table 1). The existing Chandra-HerMES area is ∼3 times larger than the existing XMM-HerMES area, making the Chandra archive a unique tool to perform our study.

Therefore, instead of new observations, we request the resources for a concerted effort to bring together all the Chandra observations that overlap with HerMES fields to compile the largest sample of QSOs at the main epoch of SMBH growth, $z = 1-3$, and to provide the most stringent constraints on their star-formation rate afforded by current data.

4. Chandra/HerMES Observational setup: The primary goal of HerMES is to trace the build up of galaxy mass using far-infrared/sub-mm observations to measure SFRs in $\sim 4 \times 10^5$ galaxies across $0 \leq z \leq 4$. The widest tier of HerMES covers the best studied extragalactic survey fields reaching $S_{250\mu m} \leq 10\,\mathrm{mJy}$ rms, close to the confusion limit. With the 100-500 μm coverage provided by *Herschel*, these data permit the separation of AGN and star formation contributions to the infrared (e.g. Hatziminaoglou et al 2010, Elbaz et al 2010).

The fields of choice are listed in Table 1 and consist of all the HerMES fields with existing Chandra coverage. The total area sums up to $\sim 15\mathrm{deg}^2$. The selected fields benefit from a large suite of multiwavelength data: Spitzer 3.6-160 μm from SWIRE (Lonsdale et al. 2003) and SERVS (PI Lacy), Herschel 100-500 μm from HerMES (Oliver et al. 2010), UV from GALEX and VISTA-VIDEO, near-infrared from UKIRT-DXS and radio from VLA/ATCA/LOFAR which in combination with the extensive spectroscopy available in most fields (Table 1) we will be able to create broad-band spectral energy distributions (SEDs) necessary to deconvolve the AGN and star-formation contribution for all the X-ray bright QSOs detected by Chandra. These complimentary data represent many thousands of hours of space-based and ground-based observing time which simply does not exist in other wide area X-ray programmes (e.g. the XMM Serendipitous Survey) or shallower *Herschel* projects (e.g. H-ATLAS).

5. Chandra/HerMES Luminous AGN: Our proposal focuses on Chandra sources with $L_X(2-10\,\mathrm{keV}) > 10^{44}\,\mathrm{erg\,s^{-1}}$ and redshifts in the range $z = 1-3$, which correspond to the main epoch of SMBH growth. Integrating the X-ray luminosity function of Ueda et al. (2003) and taking to account the (variable) depth and the area of the HerMES Chandra fields we estimate about 1600 sources in the soft band (0.5-2 keV band) and 700 in the hard band (2-10 keV band) in the luminosity and redshift intervals above. The far-IR/sub-mm detection rate of QSOs will be compared with that of less luminous AGN, $L_X(2-10\,\mathrm{keV}) = 10^{43} - 10^{44}\,\mathrm{erg\,s^{-1}}$ at $z = 1-3$ (total of 1500 expected in the 0.5-2 keV band and 500 in the 2-10 keV based in the Ueda et al. 2003 luminosity function). The combination of deep/pencil-beam and shallow/wide-area Chandra surveys ensures large numbers of sources above and below the luminosity cut of $L_X(2-10\,\mathrm{keV}) = 10^{44}\,\mathrm{erg\,s^{-1}}$. We choose to select sources in the 0.5-2 keV because of the higher sensitivity of Chandra in this band. At $z = 2$ this energy interval corresponds to rest-frame energies 1.5-6 keV and is therefore relatively unaffected by obscuration effects. Nevertheless our analysis will take this into account (see Immediate Objective section).

A large fraction of the Chandra sources in the fields of choice will have spectroscopic redshifts. These will be complemented by photometric redshift estimates either from the SWIRE optical photometry and photometric redshift catalog (Rowan-Robinson et al. 2008) or public photometric redshift estimates in selected fields (e.g. COSMOS, Salvato et al. 2009).

6. Immediate Objective: The primary goal of this proposal is to determine the processes and the sequence in which galaxies form their black holes and stars. In particular, we intend to study star formation in luminous AGN, $L_X(2-10\mathrm{keV}) > 10^{44}\,\mathrm{erg\,s^{-1}}$ in comparison with less luminous AGN, $10^{43} < L_X(2-10\mathrm{keV}) < 10^{44}\,\mathrm{erg\,s^{-1}}$ at $z = 1-3$. We will populate Figure 1 of the proposal with hundreds of sources to explore changes of the far-IR/sub-mm detection rate as a function of X-ray luminosity.

The fraction of Chandra sources with far-IR/sub-mm counterparts will be estimated by weighting each source with the maximum volume, Vmax, within which it can detected. The Vmax calculation takes into account all the selection effects, e.g. the flux limits at X-rays, infrared and optical wavelengths, the shape of the X-ray spectrum (e.g. obscuration of the AGN), the optical and infrared SED. This is to ensure that variations of the detection rate are not the result of observational biases. Photometric redshifts will also be used in the calculation by taking into account the probability density function of the photometric redshift, not just the best fit solution.

Stacking of Chandra sources at infrared/sub-mm wavelegths will also be carried out to estimate their mean infrared luminosity, place them on the $L_{SFR} - L_{AGN}$ and explore, with the largest sample possible, claims that star-formation rate and AGN activity are correlated at bright accretion luminosities.

7. Research Plan: In order to achieve the above goals in six months time, immediate availability of a large set of multi-wavelength data, most importantly X-ray and Herschel, is required as well as the expertise to handle them. Among the Co-Is there is extensive experience in reducing, analyzing and publishing Chandra survey data. The list of Co-Is includes the PIs of Chandra-COSMOS (Elvis), Chandra-SWIRE (Wilkes), Chandra Multi-Wavelength Project (Green), Chandra-EGS (Nandra), Chandra-EN1 (Nandra), and a large number of X-ray astronomers with a large publication record with Chandra data (Page, Georgakakis, Civano, Laird, Hickox). In addition, this proposal brings together the foremost experts on Herschel SPIRE data, the PI of SPIRE (Griffin), PIs of HerMES (Oliver & Bock), members of the SPIRE Instrument Control Center (Schultz, Trichas, Seymour, Vaccari) as well as experts on the multi-wavelength analysis of AGN including the PI of ELAIS and SWIRE (Rowan-Robinson) and the PI of SERVS (Lacy). As a result, the team has all the expertise required to reduce and analyze Chandra data but also immediate and proprietary access to HerMES data. The main steps toward our key science goal include:

7.1) Chandra Analysis: The data will be reanalysed using the Chandra pipeline described by Laird et al. (2009) which incorporates the Bayesian senstivity map construction of Georgakakis et al. (2008). The latter is coupled to the simple but efficient source detection methodology of Laird et al. (2009) and is designed to take into account all the observational biases that affect the detection of sources, including the Eddigton bias, the variable PSF of Chandra and vignetting. Such an accurate description of the X-ray sensitivity is essential for the proposed study,

Field	Chandra area (deg^2)	Chandra/HerMES Area (deg^2)	Total Time (ks)	Optical Spectroscopy
CDFS	0.11	0.11	4000	Silverman et al. 2010
ECDFS	0.30	0.30	250	Silverman et al. 2010
CDFN	0.12	0.12	2000	Trouille et al. 2008
EGS	0.67	0.67	1800	Coil et al. 2008
Lockman Hole	1.10	1.10	70	Huang et al. 2011
ELAIS-N1	1.50	1.50	150	Trichas et al 2010
C-COSMOS	0.92	0.92	1800	Civano et al. 2011
BOOTES	9.30	9.30	630	Kochanek et al. 2011
ELAIS-S1	0.60	0.60	160	Feruglio et al. 2008
FLS	0.35	0.35	150	Lacy et al. 2007
total	14.97	14.97	$\sim$11 Ms	

Table 1: List of all HerMES fields with Chandra coverage totaling an area of 14.85 deg^2.

which combines fields with very different characteristics in terms of depth and areal coverage. Our proposed strategy, in which fractions are estimated by weighting each X-ray source by the 1/Vmax, ensures that the complex X-ray selection function of the sample will not affect the results, i.e. any variations in the far- IR/submm detection rate of AGN with X-ray lumi- nosity. Some of the proposed fields have already been analyzeed with this method (Georgakakis et al. 2008).

7.2) X-ray Spectral Extraction: The extraction of the X-ray spectra of selected sources to estimate via spectral fits their obscuration properties, i.e. hydrogen column density. This information will be taken into account in the Vmax caclulation. The automated spectral extraction pipeline developed for the AEGIS spectral analysis (Georgakakis et al. 2010) is based on the ACIS extract (Broos et al. 2002) IDL package.

7.3) Chandra/HerMES Cross Correlation: Cross-correlation of the HerMES/Chandra data using the techniques that the Padova Data Fusion Group has developed for HerMES. The leader of the group (Vaccari) is a Co-I in this proposal. The HerMES data are immediately available to the PI as a Co-I of HerMES.

7.4) X-ray luminosity/redshift plane: Analysis of the $1 < z < 3$ population of luminous AGN on the X-ray luminosity/redshift plane utilizing the extensive spectroscopic coverage of the selected Chandra surveys. For the faintest sources we will use the photometric redshift techniques developed by the HerMES team (Rowan-Robinson et al. 2011).

7.5) Accretion & Star-formation Connection: Detailed comparison between the accretion and star-formation properties of the $1 < z < 3$ population of the $log\ L_{2-10keV} > 44$ and $43 > log\ L_{2-10keV} > 44$ AGN using the detailed SEDs created to study the HerMES sources (Rowan-Robinson et al. 2010).

Funding: In consideration of the above goals and the steps needed to achieve them, we request funds of $\sim$51K for the 6-month support of the PI (postdoc) to work on the proposed project and limited funds for collaborative and conference trips and publication costs.

References: Aird, J., et al., 2010, MNRAS, 401, 2531; Archibald E., et al., 2002, MNRAS 336, 353; Bower, R., et al., 2006, MNRAS, 370, 645; Cen, R., 2011, astro-ph/1102.0262; Coil, A., et al., 2008, ApJ, 672, 153; Croton, D., et al., 2006, MNRAS, 365, 11; Di Matteo T., et al., 2005, Nature, 433, 604; Elbaz, D., et al., 2010, A&A, 518, 29; Feruglio, C., et al., 2008, A&A, 488, 417; Georgakakis, A., et al., 2008, MNRAS, 385, 2049; Hatziminaoglou, E., et al., 2010, A&A, 518, 33; Hopkins, A. & Beacom, J., 2006, ApJ, 651, 142; Hopkins, P., et al., 2006, ApJS, 163, 1; Lacy, M., et al., 2007, ApJ, 669, 61; Laird, E., et al., 2009, ApJS, 180, 102; Lehmer, B., et al., 2009, MNRAS, 400, 299; Lonsdale, C., et al., 2003, PASP, 115, 897; Lutz, D., et al., 2010, ApJ, 712, 1287; Magorrian, J., et al., 1998, AJ, 115, 2285; Oliver, S., 2010, A&A, 518, 21; Page M., et al., 2001, Science, 294, 2516; Page M., et al., 2004, ApJ, 611, L85; Rowan-Robinson, M., et al., 2008, MNRAS, 386, 697; Rowan-Robinson, M., et al., 2010, MNRAS, 409, 2; Salvato, M., et al., 2009, ApJ, 690, 1250; Shao, L., et al., 2010, A&A, 518, 26; Silverman, J., et al., 2010, ApJS, 191, 124; Symeonidis M., et al., 2010, MNRAS 403, 1474; Trichas M., et al., 2009, MNRAS 399, 663; Trichas M., et al., 2010, MNRAS 405, 2243; Trouille, L., et al., 2008, ApJS, 179, 1; Ueda, Y., et al., 2003, ApJ, 598, 886; Wilkes, B., et al., 2009, ApJS, 185, 433

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Previous Chandra Programs & Related Publications

- "The Spectral Energy Distributions of AGN: A Shallow Survey of the ELAIS-N1 Field"
  Chandra Proposal ID06900602

1. "Testing the starburst/AGN connection with SWIRE X-ray/70 μm sources", Trichas, M., et al., 2009, *MNRAS*, 399, 663
2. "Spectroscopic identifications of SWIRE sources in ELAIS-N1", Trichas, M., et al., 2010, *MNRAS*, 405, 2243
3. "A new method for determining the sensitivity of X-ray imaging observations and the X-ray number counts", Georgakakis, A., Nandra, K., Laird, E., Aird, J., Trichas, M., 2008, *MNRAS*, 388, 1205

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EDUCATION AND APPOINTMENTS

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- UK Science and Technology Facilities Council Rolling Grant, 2007-2008
- Perren Institute Postgraduate Scholarship, 2004-2007
- UK Engineering and Physical Sciences Research Council Postgraduate Scholarship, 2003-2004
- Greek State Scholarships Foundation Fellowship, 2001-2003
- British Council Outreach Excellence Award, 2008-2009

LIST OF PROPOSAL RELATED PUBLICATIONS

1. "Suppression of star formation in powerful active galactic nuclei", Page, M., & Trichas, M., submitted to Nature
2. "The nature of submm emission from X-ray bright AGN", Trichas, M., & Page, M., submitted to MNRAS
3. "Testing the starburst/AGN connection with SWIRE X-ray/70 μm sources", Trichas, M., Georgakakis, A., Rowan-Robinson, M., Nandra, K., Clements, D., Vaccari, M., 2009, *MNRAS*, 399, 663
4. "Spectroscopic identifications of SWIRE sources in ELAIS-N1", Trichas, M., Rowan-Robinson, M., Georgakakis, A., Valtchanov, I., Nandra, K., Farrah, D., Morrison, G., Clements, D., Waddington, I., 2010, *MNRAS*, 405, 2243
5. "A new method for determining the sensitivity of X-ray imaging observations and the X-ray number counts", Georgakakis, A., Nandra, K., Laird, E., Aird, J., Trichas, M., 2008, *MNRAS*, 388, 1205
6. "Far infrared properties of known AGN in the HerMES fields", Hatziminaoglou, E., +HerMES (alphabetical order), 2010, A&A, 518, 33

PI's NUMBER OF PUBLICATIONS/CITATIONS: 39/581