The Dark side of the accretion history of the Universe
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Abstract: The study of Active Galactic Nuclei (AGN) is currently at the forefront of astrophysical research. Observations over the last decade have shown that these objects are not only important for constraining the accretion history of the Universe but they may also hold the key for understanding how galaxies evolve. Unknown parameter and a major limitation in those studies is the fraction of AGN that are hidden behind clouds of dust and gas. Those obscured sources are challenging to observe directly and as a result current constraints on their demographics suffer large uncertainties. Limitations in the data analysis methods are at the heart of the problem. Systematic and random errors have a profound impact on the interpretation of the observations and are primarily responsible for the current confused picture. We therefore propose key improvements in methodology to exploit the vast volume of available data. All the prime extragalactic X-ray and infrared surveys will be combined to minimise Poisson errors by providing AGN samples over 1 dex larger than any previous study. Bayesian inference and Monte Carlo Markov Chain methods will be developed to propagate all sources of error into the analysis and determine the space density of moderately obscured ($\mathrm{N_H} < 10^{24}\,\mathrm{cm^{-2}}$) AGN detected at X-rays. A Bayesian approach will be used to identify the distinct spectral signature in the infrared of heavily absorbed AGN ($\mathrm{N_H} \gtrsim 10^{24}\,\mathrm{cm^{-2}}$), which are missing from X-rays as a result of their extreme obscuration. Maximal constraints on the fraction of obscured AGN in the Universe will be placed by reconstructing the X-ray background spectrum using a new set of high energy AGN model spectra, which will inlcude all the key physics at play. The proposed project will therefore provide the most accurate estimate of the AGN space density as a function of obscuration, luminosity and redshift afforded by current data.

1. Motivation

Mapping Active Galactic Nuclei (AGN) in the Universe is a major challenge of current astrophysical research. We now know that a substantial, although not well defined, population of AGN is hidden behind clouds of gas and dust, which block the direct light emission of the central engine. Observations at wavelengths that are sensitive to dust could therefore lead to a biased view of the AGN demographics, with implications that go beyond the high energy astronomy community.

An accurate description of the distribution of AGN in the hydrogen column density ($\mathrm{N_H}$, parametrizes the density of obscuring clouds in front of the central engine) is essential not only to constrain the accretion history of the Universe but also to understand galaxy formation. Many lines of evidence indicate that AGN play a crucial, yet not well understood, role in galaxy evolution. Shedding light into the interplay between galaxy assembly and the growth of supermassive black holes (SMBHs) at their centres requires unbiased AGN samples. Some AGN/galaxy coevolution simulations for example, predict a heavily obscured stage for the accretion onto the SMBH (e.g. Hopkins et al. 2006). Observations that systematically miss obscured AGN would therefore reach erroneous conclusions on the relation between galaxies and their SMBHs.

2. State of the Art

Unfortunately the space density of obscured AGN remains controversial. Estimates on the fraction of mildly obscured AGN ($\mathrm{N_H} = 10^{22} - 10^{24}\,\mathrm{cm^{-2}}$) range from as low as 20% to as high as 80% of the overall population (Ueda et al. 2003, La Franca et al. 2005, Akylas et al. 2006, Della Ceca et al. 2008). This discrepancy can be partly explained if the luminosity function of obscured and unobscured AGN are very different (Burlon et al. 2011), or equivalently if the fraction of obscured AGN depends on luminosity and/or redshift (e.g. La Franca et al. 2005, Akylas et al. 2006, Hasinger 2008). However, both these trends are still debated (e.g. Dwelly et al. 2005, Dwelly & Page 2006, Wang & Jiang 2006).

Selection biases, random errors and systematic uncertainties have a strong impact on the results above and are almost certainly responsible, at least to some level, for the controversy. For example, if the uncertainties in the determination of the column density of individual sources are not properly accounted for, they may result in systematically higher $\mathrm{N_H}$ estimates for sources at higher redshifts (see Fig. 1; Akylas et al. 2006). This problem is further exacerbated by the fact that crude hardness ratios, not proper X-ray spectral analysis, are often used to estimate column densities, leading to even larger random and systematic uncertainties. Additionally, in any flux limited sample (such as the X-ray surveys above) there is an underlying degeneracy between luminosity and redshift, which is hard to disentangle (e.g. Perola et al. 2004), unless a sufficiently large sample is available and random errors are properly propagated into the calculations. Further progress in the field therefore demands a statistically robust treatment of errors, both random and systematic, to make the best use of the huge volume of data that is currently available.

Another major source of uncertainty in the determination of the $\mathrm{N_H}$ distribution of AGN is the fraction of heavily obscured sources with $\mathrm{N_H} > 10^{24}\,\mathrm{cm^{-2}}$ (Compton Thick; CT). The obscuring clouds in those systems are so dense that their detection at almost any wavelength is challenging. As a result estimates of the fraction of these systems range from few percent to over 50% of the overall obscured AGN population (e.g. Risaliti et al. 1999, Tueller et al. 2008, Akylas et al. 2009, Brightman & Nandra 2011). There has been considerable progress recently in the search for Compton Thick AGN in the mid-infrared (mid-IR; $3-24\mu\mathrm{m}$) through the detection of the thermally reprocessed radiation from the obscuring clouds of dust and gas. Many groups claim a huge population of CT AGN at the mid-IR, (e.g. Daddi et al. 2007, Fiore et al. 2008, 2009). These results are debated however, as there are indications that many (50-100%) of the claimed CT AGN are in fact compact dusty starbursts or mildly obscured Seyferts (e.g. Donley et al. 2010, Georgakakis et al. 2010, Elbaz et al. 2011, Alexander et al. 2011). The debate stems from complexity of the mid-IR wavelength regime, where both star-formation and

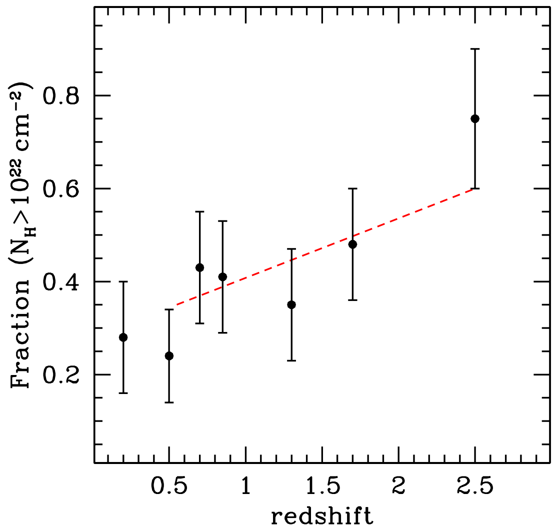

Figure 1 – Fraction of obscured ($\mathrm{N_H} > 10^{22}\,\mathrm{cm^{-2}}$) X-ray AGN as a function of redshift from Akylas et al. (2006). The data points (filled circles) suggest a strong dependence of the obscured AGN fraction on redshift. This trend however, is because of systematics. This is demonstrated by the red dashed line, which simulates what we would observe if there was *no* dependence of the obscured AGN fraction on redshift. The data are therefore consistent with *no* redshift dependence. The apparent increase of the fraction of obscured AGN with redshift is because the XMM and Chandra observe, at high redshift ($z \gtrsim 1$), rest-frame energies that are insensitive to small values of the column density ($\mathrm{N_H} < 10^{22}\,\mathrm{cm^{-2}}$). If this systematic uncertainty is not factored in the error budget the column density of unobscured or mildly obscured high redshift AGN is overestimated leading to false conclusions.

thermalised AGN light may contribute to the observed emission. Fig. 2 demonstrates this point by plotting the mid-IR spectrum of the Compton Thick QSO NGC 6240 ($\mathrm{N_H} \approx 2\times10^{24}\,\mathrm{cm^{-2}}$, intrinsic $L_X \approx 10^{44}\,\mathrm{erg\,s^{-1}}$, Vignati et al. 1999). Despite the high intrinsic luminosity of the central engine in NGC 6240, star-formation is a major component of the observed mid-IR emission (Lutz et al. 2003). In high redshift mid-IR selected samples, the decomposition of the AGN from the star-formation is challenging. Therefore the zero order hypothesis that is often adopted is that the bulk of the observed mid-IR luminosity is from the central engine. At least in the case of the prototypal CT QSO NGC 6240 this assumption is problematic. The mid-IR *is* a much promising regime for locating heavily obscured AGN, as long as a methodology is developed to account for starburst contamination.

One of the main arguments for a significant population of CT AGN is the shape of the spectrum of the diffuse X-ray Background (XRB) which is plotted in Fig. 3. It shows a hump at $\approx 30\,\mathrm{keV}$ and a power-law with spectral index $\Gamma = 1.4$ in the energy interval 2-10keV. Modeling suggests that those features can be reproduced by large numbers of CT sources (Gilli et al. 2007). This claim however, is sensitive to the adopted models for the AGN high energy spectra. Unfortunately, XRB synthesis codes have not yet adopted recent realistic simulations (e.g. Murphy & Yaqoob 2009, Brightman & Nandra 2011), which include in a self consistent way the basic physics that determine the shape of the X-ray spectrum (e.g. reflection, scattering, line emission) and current ideas on the distribution of matter close to the SMBH (e.g. torus). As a result in current XRB synthesis models key physical processes which can drastically modify the observed spectrum of AGN are either overlooked (e.g. Compton scattering, see Fig. 4) or their parameters are fixed to arbitrary values (e.g. reflection fraction). It is therefore not yet clear if the shape of the XRB spectrum requires a large population of CT AGN. There are indeed suggestions that this requirement can be significantly relaxed (e.g. Treister et al. 2009, Draper & Ballantyne 2009).

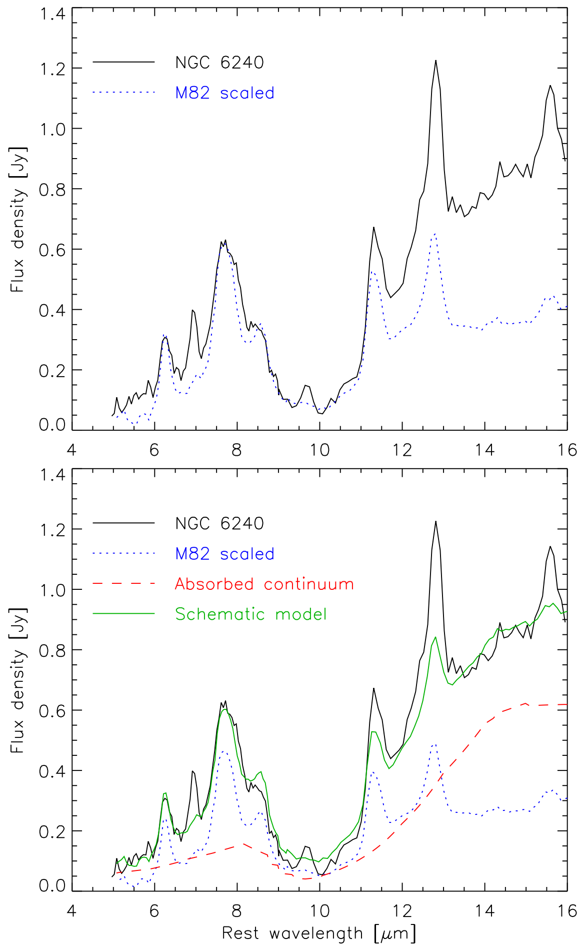

Figure 2 – mid-IR spectrum of the prototypal Compton Thick QSO NGC 6240 from Lutz et al. (2003). Although the central engine is very luminous, $L_X \approx 10^{44}\,\mathrm{erg\,s^{-1}}$, star-formation contributes substantially to the mid-IR. The observed emission can be reproduced by the sum (green solid line) of a starburst component (M 82; blue dotted line) and an absorbed power-law (red dashed line) associated with the central engine. This underlines the importance of spectral decomposition to identify AGN in the IR through the emission of hot dust in the vicinity of the SMBH.

3. The proposal

We propose to provide an unbiased census of AGN demographics at $z < 2$ and the most accurate estimate of the obscuration distribution of AGN afforded by current observations.

Methods based on Bayesian statistics will be developed to account for the systematic and random uncertainties that affect estimates of the column density distribution of mildly obscured AGN. Template fitting methods, based on the Bayesian approach, will also be developed to locate CT AGN in the infrared and separate them from starbursts. Monte Carlo simulations will be used to provide realistic and self consistent modeling of the AGN X-ray spectra. These will be combined with our estimates of the obscuration distribution of AGN to synthesize the spectrum of the XRB and explore the level at which CT sources are needed to reproduce its overall shape and normalisation.

The data that the project will use are from the publicly available observations of the prime extragalactic surveys presented in Table 1 and include selected SWIRE fields (XMM/LSS, Lockman, ELAIS-S1/N1), AEGIS, COSMOS, the Chandra Deep Field North (CDFN), the Chandra Deep Field South (CDFS) and the Extended South (ECDFS). The advantage of those fields is that they benefit from a large set of multiwavelength observations (see Table 1), including some of the deepest X-ray imaging from Chandra and XMM, UV/optical photometry from the ground and the HST, extensive optical spectroscopic programs, infrared and sub-millimeter imaging ($3.6-670\mu\mathrm{m}$) from Spitzer and Herschel. Although members of our team are involved in some of these

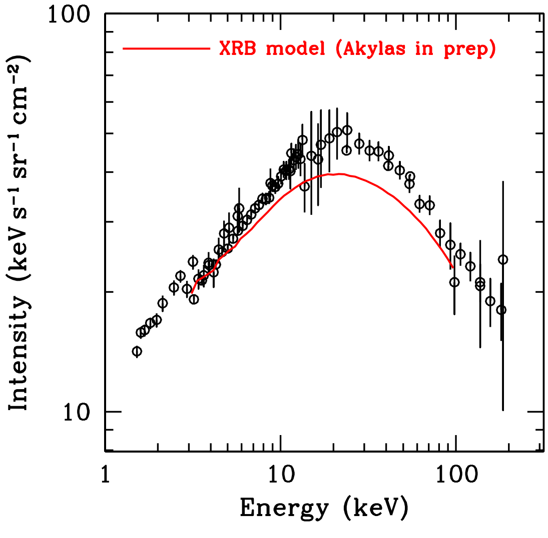

Figure 3 – The diffuse X-ray background spectrum in the energy range 1-200 keV. The black points are observations from different missions. The intensity of the XRB follows a power-law form with index $\Gamma = 1.4$ at 2-10 keV, peaks at 20-50 keV and then drops sharply at higher energies. The (red) curve is the prediction for AGN with $N_H < 10^{24}\,cm^{-2}$ from the XRB synthesis code that is developed at the National Observatory of Athens (Akylas et al. in prep). It shows that AGN with $N_H < 10^{24}\,cm^{-2}$ fall short of the XRB intensity in the range 10-50 keV. This can be interpreted as evidence for a large fraction of Compton Thick sources, $N_H > 10^{24}\,cm^{-2}$, (e.g. Gilli et al. 2007). This conclusion is sensitive to the adopted models for the X-ray spectra of AGN which are used as input to the XRB synthesis code.

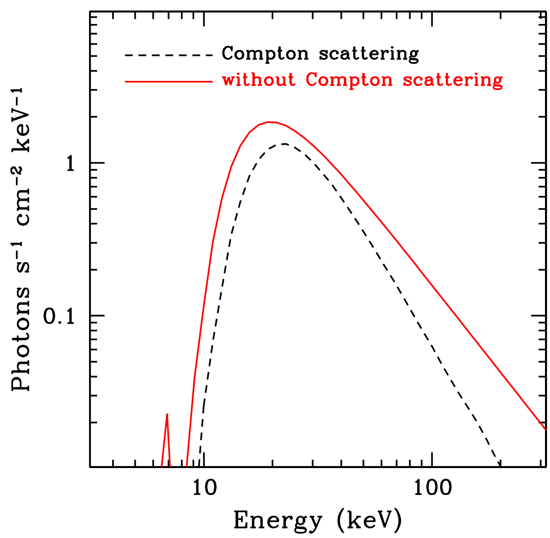

Figure 4 – X-ray spectra of Compton Thick AGN ($N_H = 5 \times 10^{24}$) from Monte Carlo simulations developed by Dr. Akylas assuming spherical symmetry (i.e. not torus geometry). The black dashed line includes the effects of both photoelectric absorption and Compton scattering. The red continuous curve includes photoelectric absorption only. It is clear that Compton Scattering has a strong effect both on the normalisation and shape of the observed spectrum.

surveys (e.g. AEGIS, XMM/LSS, Herschel programs) and therefore have access to proprietary observations, a large fraction (if not all; e.g. COSMOS, AEGIS, CDFN/S, ECDFS, SWIRE fields) of their key data, including advanced products such photometric redshifts, are already public.

Our study will primarily focus on AGN at $z < 2$, using either spectroscopic or photometric redshift estimates. Our proposed study is structured in 3 distinct but closely related directions which are described in the next sections.

3.1. The column density distribution of mildly obscured AGN

X-ray observations are the most efficient and least biased tool for locating mildly obscured AGN ($N_H < 10^{24}\,cm^{-2}$). Data from both wide-angle shallow (e.g. XMM-LSS) and small-area deep (e.g. CDFs, AEGIS) X-ray surveys will be combined and analysed in a homogeneous way using advance pipelines available to our team (e.g. Laird et al. 2009, Georgakakis & Nandra 2011). These pipelines include novel features, such as (i) a Bayesian approach for determining the spatially varying sensitivity of X-ray imaging data (Georgakakis et al. 2008) and (ii) a new parametrisation of the Point Spread Function (PSF), which improve both the source detection efficiency and the photometry. The combination of shallow/wide-area and deep/pencil-beam surveys will provide good coverage of the $L_X - z$ plane. This is essential to minimise degeneracies and explore the luminosity and/or redshift dependence of the N_H distribution of AGN. The final sample will cover almost $15\,deg^2$ on the sky (see Table 1) and is expected to include close to $\approx 10^4$ sources most of which will lie in the redshift range $z = 0 - 2$. This sample will be almost 30 times larger than any previous study in the field (e.g. Akylas et al. 2006), thereby minimising random errors. Because of the sheer volume of data a code will be developed to extract in an automated way the X-ray spectra of individual sources and then fit them with the models of section 3.3 to estimate the column density.

Emphasis will be given to the careful treatment and propagation of errors. X-ray spectral analysis (not hardness ratios) will be used for the determination of the N_H of individual sources. Bayesian statistics will be adopted to propagate random and systematic uncertainties into the analysis.

To infer the true (intrinsic) distribution of AGN in column density from the *observed* one it is essential to take into account the sensitivity of the X-ray observations. This is a complex function, as fields with variable depths and sizes are included in the analysis. A model will be developed which will parametrise the (i) intrinsic column density distribution of AGN and its possible dependence on X-ray luminosity and/or redshift, (ii) the luminosity function of AGN and its evolution with redshift. This model will be convolved with the X-ray sensitivity function to predict the *observed* column density distribution of AGN. Such an approach is essential for the interpretation of the X-ray observations because obscured AGN are more likely to drop below the detection limit of an X-ray survey.

Monte Carlo Markov Chain (MCMC) methods will be developed to find the best-fit values of the model parameters and hence constrain the true (intrinsic) distribution of AGN in $\mathrm{N_H}$. The MCMC are fully consistent with the Bayesian statistical approach and can therefore take into account all the systematic and random errors of the data. Also, the MCMC have the attractive feature that they estimate the full probability density distribution of the model parameters, thereby allowing the accurate determination of uncertainties in the case of complex problems, like the one at hand.

3.2. The space density of CT AGN

The bulk of the CT AGN population is expected to lie below the detection limit of current X-ray surveys. These sources however, can be identified through their thermal emission in the mid-IR. For that we will use data from the fields listed in Table 1, for which multiwavelength observations, including mid and far-IR photometry from both Spitzer and Herschel, are available.

The mid-IR is a complex wavelength regime as both star-formation and AGN are likely to contribute to the observed emission (see Fig. 2). One has to disentangle the two components (star-formation, SMBH accretion) to identify AGN in the IR and to estimate their bolometric luminosity.

Fig. 5 demonstrates that star-formation and AGN heat dust to different temperatures and therefore have distinct SEDs in the IR. Therefore, a powerful approach for decomposing the thermal emission of AGN from that of star-formation is by fitting templates to the observed SED. We therefore propose to develop a code that will fit a combination of starburst and AGN model templates to multiwavelength photometric data, thereby taking fully into account the complexity of the mid-IR of extragalactic sources.

The template fitting code will be based on Bayesian statistics. It will identify sources which require an AGN component at a statistically significant level to fit their mid-IR SEDs. The bolometric luminosity of the AGN component will then be estimated and the corresponding space density will be determined. This will then be compared to the space density of mildly obscured X-ray detected AGN of the same bolometric luminosity (section 3.1). Any difference will be due to CT AGN, which are missing from current X-ray surveys.

SED fitting codes, similar to those proposed here have been developed by different groups (e.g. Rowan-Robinson et al. 2008, 2009, Polletta et al. 2006). However, these codes are private. It is therefore, necessary to develop a new one, built on the expertise gained by previous studies and customised to the needs of the proposed project. We also expect to go beyond the state of the art by (i) using Bayesian statistics to determine the probability density distribution and the significance of the different SED fit components, (ii) exploring the use priors to improve the AGN detection efficiency, (iii) using the latest observational constraints on the shape of the intrinsic AGN SED (Mullaney et al. 2011).

3.3. Monte Carlo Simulations of AGN spectra

Monte Carlo techniques will be developed to produce realistic AGN spectral models which will be consistent with current observations and ideas about the structure of the matter close to SMBHs and the physical processes that contribute to the AGN high energy emission. A torus geometry will be adopted for the obscuring clouds of dust and gas. The physical processes that will be simulated are photoelectric absorption, Compton scattering, line emission, reflection of the direct AGN radiation off the torus or the accretion disk into the line of sight. The final product of this effort will be a grid of models for a slew of free pa-

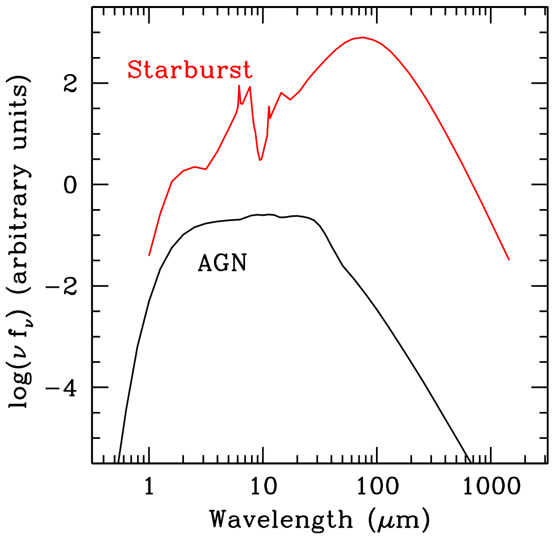

Figure 5 – Template SEDs of starburst (red) and AGN (black). The two SEDs are very different in the IR. Young stars heat the dust grains to temperatures in the range of $\approx 20-200$ K, while AGN bring the dust surrounding the accretion disk to temperatures well above 300 K. Consequently the SEDs of starburst galaxies typically peak at 100-200μm, contrary to the hot dust observed in the vicinity of an AGN torus which peaks in the mid-IR ($\approx 3-30\mu$m). The difference between the SEDs of the thermalised emission of AGN and star-formation can be exploited to decouple the two components.

rameters such as the column density of the torus ($\mathrm{N_H}$), the power-law index (Γ) and the cutoff energy (E_C) of the adopted intrinsic AGN spectrum ($f_E \propto E^{-\Gamma}\, e^{-E/E_c}$, where f_E is the photon flux density), the opening angle of the torus (θ) and the angle of the observer's line of sight relative to the torus axis (ϕ).

The spectral model grid will be used to (i) fit the X-ray spectra of individual X-ray detected AGN to estimate the column density of the obscuring torus and (ii) synthesize the XRB spectrum by modifying a code developed by our team (Akylas et al. in prep) to take the new model AGN spectra as input. The latter step will also use the constraints on the column density distribution of AGN (both mildly obscured and CT, sections 3.1, 3.2) to investigate whether they are consistent with the XRB spectrum.

Although libraries with model AGN spectra that reach the level of complexity we propose have been made public recently (e.g. Murphy & Yacoob 2009), it is essential to develop similar products to fully cover the space of parameters that are critical for the XRB. For example, a high energy cutoff is not included in the Murphy & Yacoob (2009) models although it is essential to synthesise the XRB at high energies. Similarly, the reflection of X-ray photons on the accretion disk is not included in those models although it might be a significant component of the total AGN reflected emission. The torus opening angle is also an important parameter for the XRB as it provides a physical description of the claimed luminosity dependence of the obscured AGN fraction (e.g. Akylas et al. 2006). Different opening angles are therefore required to synthesise the XRB, although in current model libraries this is not a free parameter.

4. Implementation

The proposed project will be implemented by 4 groups, which will carry out distinct but complementary research activities. The work of individual groups will be combined to determine the obscuration distribution of AGN. The contribution of each group to the proposed project is described below.

4.1 Group 1: X-ray data analysis

The 1st group (Georgantopoulos, Georgakakis, Vignali, postdoctoral external researcher) will estimate the column density distribution of mildly obscured AGN ($\mathrm{N_H} < 10^{24}\,\mathrm{cm^{-2}}$) based on X-ray observations.

The first step is to detect AGN in the X-ray fields presented in Table 1. Advanced pipelines for the reduction of X-ray observations, the detection of sources and the estimation of their fluxes are available to Group 1 of the project. Dr. Georgakakis is involved in the development of a Chandra data analysis pipeline (Laird et al. 2009) and has recently completed a similar software suite for XMM observations (Georgakakis & Nandra 2011). Unique features of those tools include (i) a simple but efficient source detection method based on Poisson statistics, which minimises spurious detections, (ii) realistic models for the X-ray telescope PSF (iii) a Bayesian approach for the estimation of source fluxes which accounts for both random and systematic errors (e.g. Eddington bias) and (iv) an accurate description of the X-ray survey sensitivity using Bayesian analysis (Georgakakis et al. 2008). The last point is particularly important as in any X-ray telescope the sensitivity

Table 1 – Fields that will be used in the proposed project

Name	X-ray Depth (seconds)	Area (deg^2)	mid and far-IR	UV/optical/near-IR	Photometric redshifts
(1)	(2)	(3)	(4)	(5)	(6)
CDF-S (Chandra)	4Ms	0.1	Herschel/Spitzer	32 bands	Cardamone et al. (2010)
CDF-N (Chandra)	2Ms	0.1	Herschel/Spitzer	6 bands	Babbedge et al. (2004)
ECDFS (Chandra)	200ks	0.3	Herschel/Spitzer	32 bands	Cardamone et al. (2010)
AEGIS (Chandra)	200ks	0.6	Herschel/Spitzer	25 bands	Barro et al. (2011)
COSMOS (XMM)	40ks	2.0	Herschel/Spitzer	30 bands	Salvato et al. (2009)
COSMOS (Chandra)	200ks	1.0	Herschel/Spitzer	30 bands	Salvato et al. (2009)
Lockman (XMM)	800ks	0.3	Herschel/Spitzer	4 bands	Rowan-Robinson et al. (2008)
ELAIS-N1 (Chandra)	5ks	1.0	Herschel/Spitzer	5 bands	Rowan-Robinson et al. (2008)
ELAIS-S1 (XMM)	70ks	0.6	Herschel/Spitzer	5 bands	Rowan-Robinson et al. (2008)
ELAIS-S1 (Chandra)	40ks	0.3	Herschel/Spitzer	5 bands	Rowan-Robinson et al. (2008)
XMM/LSS (XMM)	10ks	9.0	Herschel/Spitzer	5 bands	Rowan-Robinson et al. (2008)

The columns are: (1): X-ray field name and in brackets X-ray telescope that the data are from; (2): Total exposure time per pointing in each field; (3) Area in deg^2 of each field; (4) mid and far-infrared data availability; (5) number of UV, optical and near-IR bands available in each field; (6) reference for photometric redshift estimation.

to sources of a given flux is a strong function of position on the detector.

We emphasize the need to reduce the X-ray data from scratch to produce new uniformly selected X-ray source catalogues. Although many groups have published X-ray source lists in the fields of choice, they are unavoidably heterogeneous in nature. The basic data reduction steps, the source detection algorithms and thresholds, the definition of the energy bands within which sources are extracted, the methodology for determining the sensitivity of the X-ray observations differ among groups. The proposed project will produce uniform X-ray data products, in addition to the benefits of using the unique features of the pipelines available to our group (e.g. sensitivity estimation).

Based on the observed X-ray source count distribution (e.g. Georgakakis et al. 2008), we anticipate a total of about 10^4 X-ray detections at the depth and area coverage of the X-ray fields. X-ray sources will be identified with optical/infrared counterparts using the multiwavelength data in the fields of choice. These include UV, optical, near- and mid-IR imaging in the form of band-merged catalogs (e.g. Rowan-Robinson et al. 2008 for SWIRE fields, Cardamone et al. 2010 for the ECDFS). Statistical methods designed to minimise spurious counterparts and maximise the fraction of X-ray identifications will be employed (e.g. Brusa et al. 2007, Georgakakis et al. 2009, Georgakakis & Nandra 2011). Photometric or spectroscopic redshifts are also available for most X-ray AGN with optical counterparts in the surveyed fields, e.g. close to 100% in COMSOS (Salvato et al. 2009, Brusa et al. 2010), ECDFS (Cardamone et al. 2010) or AEGIS (Barro et al. 2011). Where needed the Bayesian photometric redshift code PBZ (Benitez 2000) will be applied to the available photometry to determine redshifts.

Next, algorithms will be developed to extract and fit with models the X-ray spectra of all X-ray sources in the selected fields. Because of the large number of sources ($\approx 10^4$) the code will have to be automated with minimum human intervention. At the fitting stage we will use the model AGN spectral grid which Group 2 will develop (see section 4.2 below). It is recognised that the parameter space of that spectral grid is too large for this particular application. Many of the detected sources will have too few counts to allow constraints on all the free parameters of the spectral library. Some of those parameters will therefore be fixed to realistic values (e.g. opening angle of the torus, line of sight, cutoff energy, power-law index). The full probability density function of the estimated parameters (e.g. column density) will be used, not just the best-fit solution. In this way errors will be propagated into the analysis. Dr. Georgantopoulos has developed specific expertise in the interpretation of AGN X-ray spectra and the search for heavily obscured sources (e.g. Georgantopoulos et al. 2008, 2009). Therefore, he will lead the X-ray spectral analysis for the proposed project.

The small number of X-ray detected Compton-thick AGN ($\mathrm{N_H} > 10^{24}\mathrm{cm}^{-2}$) will also be searched for and identified at this stage. These objects are expected to represent only about 1% of the X-ray source population at the X-ray flux limits of the selected fields. Nevertheless, their direct detection will have a strong impact on the determination of the true (intrinsic) fraction of Compton Thick sources. The identification of such AGN is among the main research interests of Dr. Vignali, the senior staff visitor of Group 1. We budget for a total of 3 months visit for Dr. Vignali to the National Observatory of Athens. This is to familiarise himself with the use of the X-ray source catalogue that will be developed as part of the proposed project and to apply his expertise in the search of X-ray detected Compton Thick AGN.

The post-doctoral external researcher of Group 1 will develop the model to interpret the *observed* $\mathrm{N_H}$ distribution of AGN and to infer their true (intrinsic) distribution to column density. The detection of an AGN at a given X-ray flux limit depends in a complex way on (i) its column density (i.e. obscured sources appear fainter at X-rays), (ii) its luminosity and redshift (intrinsically faint sources are hard to detect at high redshift) as well as (iii) the instrumental setup (i.e. sensitivity of the X-ray observation). Therefore the interpretation of the observed $\mathrm{N_H}$ distribution of AGN requires modeling of those effects. In this approach a function form is adopted which describes with a set of parameters how the space density of AGN depends on luminosity, $\mathrm{N_H}$ and redshift. This model function when folded through the telescope sensitivity should reproduce the observed number of AGN as a function of N_H, L_X and z.

The statistical modeling will use the Monte Carlo Markov Chain (MCMC) technique to estimate the probability density function of the free parameters (e.g. intrinsic column density distribution, z/L_X dependence). Bayesian model comparison will also be performed to explore for example, if models that include z and/or L_X dependence of the obscured AGN fraction (e.g. Hasinger 2008, Burlon et al. 2011) provide better description of the data at a statistically significant level.

The statistical methodology will be developed by Group 4 (see section 4.4 below) in close collaboration with Group 1 (Georgakakis, external researcher). The post-doctoral fellow of Group 1 will implement the adopted statistical methodology in a code and will apply it to the X-ray data.

We budget for 2 years' salary for the postdoctoral external researcher.

4.2 Group 2: Monte Carlo simulations

Group 2 (Mastichiadis, Vlahakis, Akylas, post-doctoral external researcher) will lead the development of the AGN X-ray spectral model grid. This will be based on Monte Carlo simulations which will take into account recent ideas on the geometry and the distribution of mass around the SMBH as well as the key physical processes that are believed to shape the spectra of AGN. The grid will be used by Group 1 to fit the observed spectra of X-ray sources and determine their column density. It will also be used by the code that will be developed by Group 1 to infer the true (intrinsic) $\mathrm{N_H}$ distribution of AGN based on the observed one. Finally, the AGN spectral library will be employed for the reconstruction the spectrum of the diffuse X-ray background at energies 2-100 keV to assess the level at which Compton Thick sources are needed to explain the peak at $\approx 30\,\mathrm{keV}$.

The external researcher (post-doc) of Group 2 will be responsible for the development of the Monte Carlo code under the supervision of Drs Mastichiadis and Vlahakis. The first step is to parametrise the geometry of the problem, i.e. torus, accretion disk. Next, the physical processes for the interaction of matter and radiation will be introduced. A photon emitted from the central source will be allowed the following options. It may be (i) absorbed or (ii) scattered into a different direction (Compton scattering) by the torus, (iii) reflected off the torus or the accretion disk, (iv) ionise the matter to produce emission lines, the most prominent of which is the Fe Ka at 6.4 keV, (v) escape without any interaction. The shape of the observed spectrum is therefore determined by the geometry of the problem (i.e. torus opening angle θ, angle ϕ between the line of sight and the torus axis), the density of the torus material (parametrized by its column density $\mathrm{N_H}$) and the shape of the intrinsic AGN spectrum which can be approximated by a power-law with index Γ modified by an exponential cutoff at energies above E_c ($f_E \propto E^{-\Gamma}\, e^{-E/E_c}$, e.g. Gilli et al. 2007).

The Monte Carlo simulations will follow monoenergetic photons through the toroidal reprocessor. A large number of photons will be generated and the fate of each one will be determined by random numbers based on the relative cross sections of the different physical processes (absorption, scattering, reflection, line emission) and the column density of the torus. For each set of parameters N_H, θ, ϕ, the output spectrum of the monoenergetic photons will be stored using the Green's functions. The integration of those functions allows the reconstruction of the reprocessed X-ray spectra of arbitrary intrinsic (input) AGN spectra, i.e. for any pair (Γ, E_c) in the case of a power-law with an exponential cutoff. The use of Green's functions therefore reduces the number of free parameters in the Monte Carlo simulations to three (N_H, θ, ϕ). The Monte Carlo code will be parallelised to take advantage of the shared memory multi-CPU computers of the University of Athens (HP 9000/SD64 64 CPUs 40GB RAM, HP V2600 32CPUs 16GB RAM).

Dr. Vlahakis' expertise in the modeling of physical processes with complex geometry (e.g. hydrodynamical simulations of jets) will help setting up the basic geometrical structure of the proposed simulations (torus, accretion disk). Dr. Mastichiadis' research focuses on the interaction between matter and radiation, particularly at high energies. He will advice the post-doctoral fellow with the coding of the physical processes that govern the interaction of X-ray photons with the torus and the accretion disk. Dr. Akylas combines observational and modeling expertise in the study of AGN X-ray spectra. His input and advice will ensure that the grid of model AGN spectra that Group 2 will develop fulfills the observational requirements of the proposed project (e.g. energy range of the model spectra, parameter space).

Dr. Akylas has also developed a code for the synthesis of the diffuse X-ray background (see Fig. 3). This will be modified to use as input the AGN model spectra library described above and the observational constraints on the column density distribution of X-ray AGN that Group 1 will provide. The updated XRB code of Dr. Akylas will be used to assess the level at which Compton

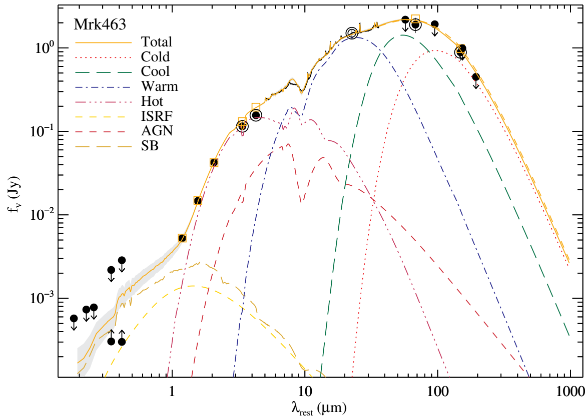

Figure 6 – Decomposition of the observed SED of the nearby active galaxy Mrk 463, shown in orange, using the model of Marshall et al. (2007). The dust components of different temperatures are marked in addition to the contribution from the AGN and the photospheres of a circumnuclear starburst component (SB). This method depends strongly on the availability of mid-IR spectra in order to fit the PAH emission and 9.7m Si feature. It is therefore not optimised to fit sources for which only photometry is available. We propose to expand on the Marshall et al. approach and develop an SED fitting code which will be applied to the large samples of IR selected sources in the deep extragalactic surveys to quantify the AGN contribution to their bolometric luminosity.

Thick AGN are required to explain the intensity of the XRB close to its peak at about 30 keV. The required number of Compton Thick sources (in excess of those already observed at X-rays) will be compared with the results of the Group 3 on the identification of heavily obscured AGN in the IR.

We propose to employ a postdoctoral external researcher for 2 years to develop the Monte Carlo simulations.

4.3 Group 3: Selecting IR AGN

Group 3 (Charmandaris, Xilouris, Le Floc'h, Magdis, Trichas, postdoctoral external researcher) will develop an SED template fitting tool to identify heavily obscured AGN, including Compton Thick ones, among mid-IR selected sources in the fields listed in Table 1. The selected fields benefit from large multiwavelength datasets, including UV, optical, mid- and far-IR from both Spitzer (3.6, 4.5, 5.8, 8.0, 24, 70, 170μm) and Herschel (70, 110, 160, 250, 350, 500μm). Members of Group 3 (Charmandaris, Le Floc'h, Magdis, Trichas) are involved in all the main Herschel programs that will survey the fields of choice (HERMES, PEP, HERSCHEL-GOODS). It is therefore expected that advanced data products, including the latest band-merged photometric catalogues will be available to the group.

A code will be developed to fit a combination of a small number (about 10) of templates (e.g. AGN, starburst, evolved stellar population) to the multiwavelength photometry of extragalactic sources. Dust heated by stellar processes and AGN have distinct SEDs, which peak at very different wavelengths (see Fig. 5). Therefore the proposed method has the potential to decouple different spectral components and identify sources which require the AGN template at a statistically significant level to reconstruct the observed IR SED. Bayesian statistics will be used to (i) study the effect of priors in the efficiency of identifying AGN in the IR (i.e. it is known that the fraction of AGN increases with IR luminosity, Sanders & Mirabel 1996) and (ii) quantify the statistical significance of the different templates used in the fit.

As a first step we propose to calibrate the code on X-ray sources for which it is known they host AGN. This will allow tuning of the various input parameters of the code (templates, priors etc) to maximise the efficiency of detecting AGN in the IR. We will then apply the code to the Herschel $70\mu\mathrm{m}$ selected catalogue. This is to ensure at least one far-IR datapoint on the SED to get a handle on the level of star-formation and hence the contribution of this component to the mid-IR. A total of 12 000 $70\mu m$ sources are expected within the fields of choice, the vast majority of which also have counterparts at the shorter Spitzer wavelengths ($3.6 - 24\mu\mathrm{m}$).

A byproduct of the fitting code will be the mid-IR luminosity of the AGN component, if present, which can then be converted with good accuracy (Lutz et al. 2004) to intrinsic X-ray luminosity (i.e. not absorbed by the torus of gas and dust). The space density of IR AGN at a given intrinsic luminosity will be compared with that of X-ray AGN at the same intrinsic luminosity. Any difference will be because of Compton Thick AGN, which are systematically missed at X-rays but can be picked out in the mid-IR.

The X-ray properties of the IR selected AGN will also be explored. This is important for planning surveys of upcoming X-ray missions (NuSTAR, eROSITA, launch 2012) and setting the specifications for new X-ray telescopes (ATHENA, New Hard X-ray Mission), all of which have among their prime goals the direct detection of heavily obscured and Compton Thick AGN at X-rays.

Because of the faintness of the heavily obscured sources in the 0.5-10 keV band, where XMM and Chandra operate, we anticipate that most IR AGN will lie below the detection limit of the X-ray observations. X-ray stacking techniques will therefore be used to explore the mean X-ray properties of IR selected AGN (X-ray luminosity, X-ray spectrum). Such methods have been extensively used to study at X-rays populations of extragalactic sources which are too faint to be individually detected in current X-ray surveys (e.g. Georgakakis et al. 2003, Georgantopoulos et al. 2008, Fiore et al. 2008, 2009). We will use the Bayesian stacking code of Blocker et al. (2009), which is superior to traditional stacking methods, to constrain the mean X-ray properties of IR AGN. We will also investigate if they are consistent with those expected for Compton Thick sources: (i) observed (absorbed) X-ray emission suppressed by at least 1-2 dex relative to the IR luminosity (e.g. Lutz et al. 2004), (ii) a strong Fe Ka 6.4 keV line (e.g. Brightman & Nandra 2011) and (iii) X-ray continuum approximated by a flat power law ($\Gamma \approx 0$, contrary to non-absorbed sources where $\Gamma \approx 1.9$) because of photons reflected in our line of sight from the torus and/or the accretion disk (Georgantopoulos et al. 2008).

The proposed project builds upon the expertise of Prof. Charmandaris in SED template fitting methods. With his collaborators he has extensively used this technique either to elucidate the energy source (AGN vs star-formation) in dust enshrouded galactic nuclei (see Fig. 6; Marshall et al. 2007) or to infer physical properties of star-forming galaxies (see Fig. 7; da Cunha et al. 2010). Dr. Xilouris has developed an elaborate radiative transfer code to fit and interpret the far-infrared SED of extragalactic sources. Together with Dr. Le Floc'h he will contribute to the selection of the appropriate set of templates which will be used in the fitting code. The goal is to provide the smallest possible set of templates, which in combination will be able to reproduce the com-

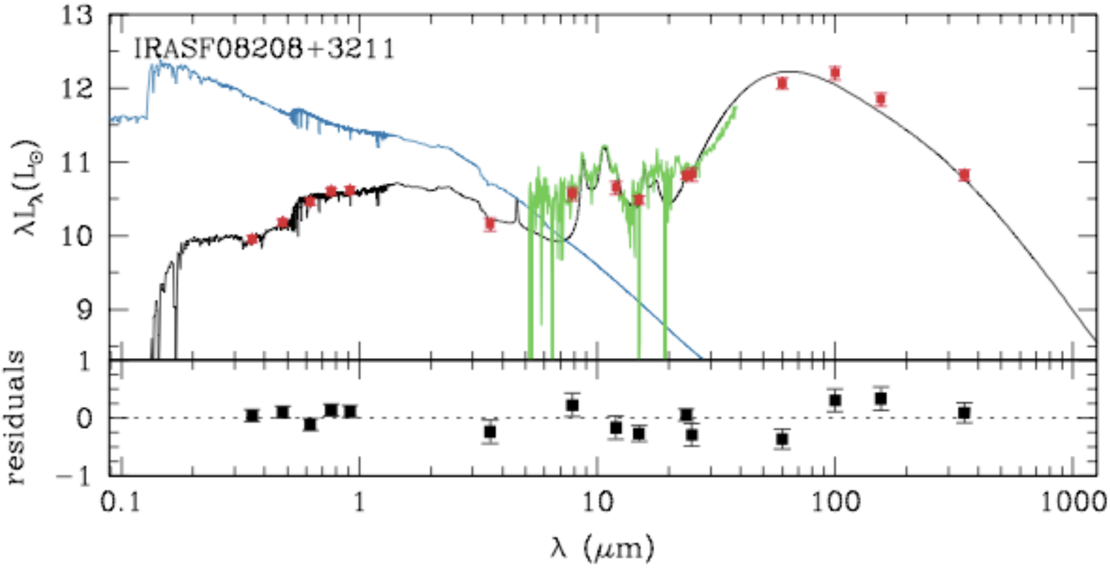

Figure 7 – The observed SED (red points and green line) of the ultraluminous infrared galaxy IRASF08208+3211. The black curve is the model SED fit presented by Da Cunha, Charmandaris et al. (2010). The cyan curve corresponds to the intrinsic (extinction corrected) model SED of the stellar populations which heat the dust. The methodology of Da Cunha et al. is specifically developed to use Bayesian approach on a set of priors to fit the observed photometry from the UV to the far-IR and applying energy balance to estimate a wealth of physical properties of the system. Despite its power to probe the properties of dusty star forming systems the da Cunha et al. model does not account for the contribution of an AGN to the observed SED. The proposed project will build on the experience gained from the Da Cunha et al. work to develop a Bayesian SED fitting code that will include templates for AGN to identify heavily obscured active SMBH in the mid-IR.

plexity of the IR SED of extragalactic sources. We budget for a 3 month visit of Dr. LeFloc'h to work with Drs Xilouris and Charmandaris on the selection of model templates.

The two external advisors of Group 3, Drs Magdis and Trichas, are members of the HermMES and PEP collaborations which use data from the SPIRE and PACS instruments of Herschel. They are therefore experienced both with the calibration of those instruments and with the raw data reduction methodology. Although the Herschel data that Group 3 will use will be in the form of photometric source catalogues, specialised knowledge on the intricacies and limitations of the HermMES/PEP datasets as well as a good understanding of the SPIRE/PACS instrument characteristics are essential for the proposed project. Key issues on which the expertise of Dr. Mardis and Dr. Trichas is needed include: (i) the flux limit of different Herschel wavebands and possible spatial variations across the surveyed fields, (ii) the photometric accuracy of the catalogues, (iii) the shape and size of the Point Spread Function, (iv) the astrometric accuracy of the source positions, (v) the estimation of reliable upper limits in the case of non-detections. We request funding for two brief (5 day) visits of each of the two experts at the University of Crete.

Dr. Papadakis is an experienced X-ray astronomer and he will lead the study on the X-ray properties of IR AGN via stacking analysis.

Salary for three years is requested for the postdoctoral external researcher of Group 3 to develop the SED fitting code and apply it to the data.

4.4 Group 4: Statistical Methodology

Group 4 (Meligkotsidou, Vrontos, PhD external researcher) will lead the development of suitable Bayesian methodology for the interpretation of the X-ray data of Group 1 to determine the intrinsic column density distribution of X-ray AGN. The statistical tools that will be developed include:

(i) the derivation of the likelihood function for a given model that describes the space density of AGN as a function of column density, luminosity and redshift. The likelihood function is the joint distribution of the observations and can be modified to take into account the systematic and random errors of the data in the form of probability density functions.

(ii) The choice of the appropriate prior distributions for the unknown model parameters. The assumption of constant (or log-constant) priors for the parameters over the range of plausible values is a good starting point. We will also experiment with more complex schemes, e.g. normal or log-normal distributions.

(iii) The use of Markov Chain Monte Carlo (MCMC) techniques to draw samples from the posterior distribution of the unknown parameters to infer their probability density functions.

(iv) The Bayesian model comparison based on calculating the posterior probabilities of various competing models. For example, are models which include redshift and/or luminosity dependence of the AGN $\mathrm{N_H}$ distribution favored by the data?

The steps above require knowledge of advanced methods of Bayesian inference and computational statistics. Dr. Meligkotsidou and Dr. Vrontos are among the few Greek researchers with extensive experience in that field of applied mathematics. They will supervise the external researcher of Group 4 (doctoral student), who will develop the appropriate methodology for the analysis of the observed data, as part of his/her PhD thesis. It is essential that the PhD student has a good understanding of the astrophysical part of the problem (e.g. spatially varying sensitivity of the X-ray detector, systematic and random uncertainties in the determination of the $\mathrm{N_H}$ for individual sources). For this purpose, Dr Georgagakis and the external researcher of Group 1 (postdoctoral fellow with astrophysical background) will closely monitor the progress of the PhD student and advise him/her throughout the project.

We budget for 3-year salary for the external researcher of Group 4 to complete his PhD.

5. Work Packages

The proposed proposed is organised into Work Packages (WP). These are described below for each group.

Group 1

Leader: Georgantopoulos (National Observatory of Athens, NOA).

Members: Georgakakis (NOA), Vignali (Bologna), post-doctoral external researcher.

WP1.1, X-ray data reduction & optical identification: Production of the X-ray source catalogues of the selected fields using the pipelines available to NOA for XMM and Chandra. Matching of the X-ray sources with the multiwavelength observations in the fields of choice. Estimation of photometric redshifts (implementation: Georgakakis).

WP1.2, Estimation of the column density of X-ray AGN: Development of the code that will extract the X-ray spectra of AGN and fit them with the models of WP2.1 to estimate the $\mathrm{N_H}$ of individual sources (implementation: Georgantopoulos, Vignali).

WP1.3, Column density distribution of X-ray AGN: Design the code that will estimate the intrinsic $\mathrm{N_H}$ distribution of mildly obscured AGN ($\mathrm{N_H} < 10^{24}\,\mathrm{cm^{-2}}$). The model will be based on Bayesian methodology developed in WP4.1 (implementation: NOA postdoc).

Group 2

Leader: Mastichiadis (University of Athens, UoA).

Members: Akylas, Vlahakis (UoA), postdoctoral external researcher, Akylas (NOA external advisor).

WP2.1, Monte Carlo simulations: The design of the Monte Carlo simulations to produce the AGN model spectral library (implementation: UoA postdoc, Mastichiadis, Vlahakis).

WP2.2, XRB synthesis: The spectral models of WP2.1 will be included in the XRB synthesis code that Dr. Akylas has developed to assess the level at which CT sources are required to reproduce the XRB spectrum. The code will be modified to include the results of WP1.3 (implementation: Akylas).

Group 3

Leader: Charmandaris (University of Crete, UoC).

Members: Papadakis (UoC), Xilouris (NOA), LeFloc'h (CEA/Saclay) , Magdis (Oxford, external advisor), Trichas (Harvard/CfA, external advisor), post-doctoral external researcher.

WP3.1, SED fitting code: The development of the Bayesian code that will fit the infrared SEDs of extragalactic sources with a combination of templates (implementation: UoC postdoc).

WP3.2, Estimation of the space density of CT AGN: Identification of infrared AGN and estimation of their space density. Comparison with the space density of X-ray AGN (implementation: UoC postdoc).

WP3.3, X-ray properties of infrared AGN: Stacking will be used to explore if the infrared AGN have X-ray properties consistent with CT obscuration (implementation: Papadakis)

Group 4

Leader: Meligotsidou (UoA, Dept. of Applied Mathematics).

Members: Vrontos (Athens University of Economics and Business), external researcher (PhD student).

WP4.1, Bayesian Methodology: The group will develop the statistical methodology (MCMC, Bayesian approach) that will be used in WP1.3 (implementation: UoA PhD student).

5. Impact and Added Value

The determination of the column density distribution of AGN is a long standing astrophysical problem with implications on diverse research fields such as (i) the role of SMBHs in the formation and evolution of galaxies, (ii) the accretion history of the Universe, (iii) the origin of the SMBHs at the centres of all bulges in the local Universe, (iv) the AGN Unification paradigm.

It is not a coincidence that many high profile space missions that are currently in orbit or are planned for the future have the theme of the proposed program among their main science goals: e.g. Chandra, XMM, NuSTAR (launch 2012) and eROSITA (launch 2012) at X-rays and Spitzer, Herschel, SPICA (launch 2018) and the JWST (James Webb Space Telescope, launch 2016) at the infrared.

It is envisaged that the proposed project will have a strong impact to the astronomy community. This is because we plan to (i) assemble the largest dataset ever used for such a study by combining data from all the prime extragalactic surveys and (ii) develop and use advanced statistical methods to analyse them. The statistical methods we propose to develop will account for all sources of error, both random and systematic, which are primarily responsible for the current confusing and contradictory picture on the fraction of obscured AGN in the Universe. The proposed program is not just incremental improvement in analysis methods but has the potential to revolutionize the established picture in the proposed field. It is not surprising that the few studies that account for some of the effects we propose to quantify (Dwelly et al. 2005, Dwelly & Page 2006), reach very different conclusions on the obscuration distribution of AGN from studies that tend to overlook random errors and systematics.

In addition to the main goal of the proposed study, the analysis tools we will develop are expected to have an impact on other fields of astronomy. For example, the Bayesian template fitting code for the identification of IR AGN can also be used to infer physical properties of AGN host galaxies, such as their stellar mass and star-formation history. These properties have been shown to be a powerful diagnostic of the physics that drive the growth of SMBHs and their relation to the formation of galaxies (e.g. Georgakakis et al. 2009, Georgakakis & Nandra 2010, Silverman et al. 2009).

The state-of-the-art AGN spectral models we propose to develop will also be a unique resource to the entire community for interpreting the high energy spectra of AGN to infer physical properties related to active SMBHs.

The proposed synergy of astronomers and statisticians has the potential to provide much needed novel statistical analysis methods to the entire high energy astrophysics community. X-ray astronomy has witnessed an explosion in the quality and volume of observational data in the last decade. At the same time however, the statistical techniques used to analyse those observations have hardly evolved, with direct implications in the quality of results and conclusions. The proposed improvement in methodology is particularly timely since upcoming and future missions (e.g. eROSITA, NuSTAR, ATHENA) will soon set new standards in the quality and quantity of astronomical data.

The participating groups have already established themselves in their research fields. The proposed program will help them reaffirm their positions at the international level and will offer them the opportunity to share expertise and to carry out cutting edge research which is over and above the capabilities of individual partners outside the proposed collaboration. We envisage that the results and the data products of the proposed research program will become the reference point for AGN studies for many years to come.

6. Management Structure

The proposed project relies heavily on the complementary skills of the 4 groups. It is therefore essential to ensure that appropriate procedures are adopted to maximise the collaboration between the groups and manage effectively the research of individuals.

The management of the project will be the responsibility of the supervisory board. It will consist of the project coordinator (Georgakakis) and the leaders of the 4 groups (Georgantopoulos, Charmandaris, Mastichiadis, Meligotsidou). They will monitor the progress of individual work packages, ensure the effective coordination of groups, identify possible risks and take actions to mitigate them. During teleconferences held once every month, the group leaders will report on the progress of their group research and discuss any problems encountered. The supervisory board will then decide on actions that should be taken to resolve problems and address other risks or delays. The minutes from these meetings will be circulated to the project researchers via email. The group leaders will enusre that the actions decided by the supervisory board are implemented at the group level. The supervisory board will also be responsible for recruiting the project researchers.

Project workshops will be organised twice per year. The goal of these 2-day event will be to review the progress of the research program, encourage the collaboration between individuals and plan for the future. There will be talks on the latest results and analysis techniques, presentations on new ideas as well as discussion groups on existing problems and open questions. Sessions dedicated to future plans will also be organised. The small number of participants will create an informal atmosphere that will promote the interaction and in depth discussions. In addition to the project members there will be a small number (≈ 5) of external invited researchers, aiming at bringing in fresh ideas, different perspectives and criticism to the project research. Formal meetings of the supervisory board will also take place during the project workshops. This is an opportunity for in depth discussions of the overall progress of the project and for long term planning.

We also propose to organise an Advanced Astronomy School, which will last for 5 days and will be open to Ph.D. students and early post-docs from outside the proposed project. External experts will also be invited to lecture at this event. The aim is to offer the participants (and foremost the project researchers) a broad perspective of the overall research on AGN. This will help them view their own project in a larger framework. They will also gain practical experience on specialised software (e.g. for data reduction), advanced analysis methods (e.g. fitting models to X-ray spectra) and high performance programming (e.g. Monte Carlo simulations), which they will almost certainly use in their research.

A wiki page will also be set up for the project. This interface offers an alternative and efficient method of exchanging knowledge and sharing information within the network. The progress of various projects, the availability of advanced data products, the development of novel analysis techniques and tools, can all be communicated easily to the entire network through a wiki page. We also envisage discussion forums where questions and problems from the network participants can be posted and answered. This will facilitate the transfer of knowledge and improve the interaction between researchers.

7. Quality of the groups

Our team includes some of the leading Greek experts at X-rays, the infrared, high energy radiation processes and applied mathematics. All of them are prolific and high h-index scientists who have been recognised at the international level for their contribution in their fields expertise.

It is the ambition of the proposed project to bring together the diverse and complementaty skills of individual group members to carry out world class research in one of the most active and competitive fields of current astrophysical research.

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