THE DOMINANT ENERGY SOURCE OF ULTRALUMINOUS INFRARED GALAXIES (ULIRGS)

1 Introduction - the Importance of ULIRGs

Ultraluminous Infrared Galaxies (ULIRGs), defined as galaxies with $L_{IR} = L(8-1000\ \mu m) \geq 10^{12} L_\odot$ (H_0 = 75 km s^{-1} Mpc^{-1}, $q_0 = 0$; this luminosity limit is equivalent to the minimum bolometric luminosity of a QSO) are one of the most important discoveries of the *IRAS* satellite. At luminosities above $10^{12} L_\odot$, the space density of ULIRGs in the local universe is greater than that of optically selected quasars with similar bolometric luminosities by a factor of ~ 1.5. Thus ULIRGs represent the most common type of ultraluminous galaxy. Systematic ground-based optical observations have shown that ULIRGs are almost always undergoing mergers (e.g., Sanders et al. 1988, ApJ, 325, 74). Sanders et al. (1988) suggested that these objects represent a dust-enshrouded phase that eventually evolves into optically-selected quasars. If this is true, ULIRGs take on a fundamental importance for the origin and evolution of quasars.

ULIRGs in the local universe may be compared with submm sources at $z = 1-4$ discovered with SCUBA (e.g., Smail et al. 1997, ApJL, 490, L5; Hughes et al. 1998, Nature, 394, 241). The mean properties (L_{IR}, M_{H_2}, near-infrared colors) of the two classes are remarkably similar. Integration of the light from the IRG/SCUBA population shows that it may account for most or all of the submm/far-infrared background, as a result of the strong cosmological evolution of these sources (e.g., Chapman et al. 2005, ApJ, 622, 772).

Observations with Chandra and XMM have confirmed the suggestion of Setti & Woltjer (1989, A&A, 224, L21) that the X-ray background is made up of active galaxies with a wide range of absorbing column densities. Low column density objects (Seyfert 1s and QSOs) dominate at soft energies, while heavily absorbed nuclei (N_H up to 10^{24-25} cm^{-2}) take over at energies above several keV. These latter objects are similar to, but more luminous than, the known heavily absorbed objects at low redshift (e.g. NGC 1068, NGC 4945, Circinus). The net effect is a hard background spectrum that coincidentally mimics the previously postulated thermal spectrum with a rollover near 40 keV. There is a general consensus that all these X-ray luminous objects are powered by accretion onto a supermassive black hole (SMBH). However, the SCUBA upper limits on their flux are not sufficiently stringent to say whether they are LIRGs or ULIRGs.

ULIRGs are fundamentally relevant to a wide range of astronomical issues, including the role played by galactic mergers in forming some or all elliptical galaxies (Genzel et al. 2001, ApJ, 563, 527; Veilleux et al. 2002, ApJS, 143, 315), the efficiency of transport of gas into the central regions of such mergers, the subsequent triggering of circumnuclear star formation, the resulting heating and metal enrichment of the IGM by "superwinds" (e.g. Veilleux et al. 2005, ARAA, 43, 769), the potential growth and fuelling of SMBHs and the possible origin of quasars. These objects are also relevant to the dominant source of radiant energy in the universe today. Star formation at an average $< z > = 1.5$ or accreting SMBHs at $< z > = 2$ may each provide essentially all the present-day energy density in the cosmic FIR + NIR + UV backgrounds (e.g., Heckman 1999, Ap&SS, 266, 3). Thus while the present-day ULIRGs make a relatively small contribution to the total present day light, their cousins at high z are fundamentally important in this regard.

2 Energy Source of ULIRGs

From the above discussion, it is clear that the high redshift ($z \sim 2$) cousins of ULIRGs are fundamental to many cosmological problems. Study of these high redshift galaxies is, however, very difficult because of their faintness, so the most useful approach is to understand first the present-day ULIRGs. But then we immediately encounter a fundamental problem: are ULIRGs powered by starbursts or accretion onto SMBHs? As noted, this problem in the **local** universe is fundamental to issues on **cosmological** scales. The power source has been the subject of a lively debate for several years (e.g., Ringberg's "Great Debate:" Joseph 1999, Ap&SS, 266, 321; Sanders 1999, Ap&SS, 266, 331). The main arguments are as follows:

• **In Favor of Starbursts**. Optical and near infrared spectra of the 1 Jy sample (Veilleux et al. 1999ab, ApJ, 522, 113 & 139) show starbursts in almost all galaxies, while $\sim 30\%$ show evidence for AGNs. Even in the mid-infrared, with greatly reduced extinction, only $20-30\%$ of the ULIRGs may be powered predominantly by an AGN (ISO: e.g., Genzel et al. 1998, ApJ, 498, 579; Lutz, Veilleux, & Genzel 1999, ApJ, 517, L13; Spitzer: e.g., Veilleux et al. 2006, in prep.). Massive central gas disks, commonly associated with starbursts, are found. Starburst models based on these data can account for most of the bolometric luminosity in most objects. The existence of a correlation between far-infrared, Br γ and radio continuum luminosities favors a starburst. Radio and X-ray observations tend to show luminosities consistent with known correlations for starbursts in most cases.

• **In Favor of AGNs**. There is a clear trend of more Seyferts and AGN-like objects with increasing L_{IR} (e.g., Veilleux et al. 1999ab; Lutz et al. 1999) such that most of the objects with $L_{IR} \gtrsim 10^{12.3} L_\odot$ and/or "warm" infrared colors

($f_{25\mu m}/f_{60\mu m} > 0.2$) are likely dominated by an AGN. For the nearest 5 ULIRGs (thus the best studied), the radio (high T_b core), mid-infrared (PAH line to continuum ratio), optical and near-infrared (Seyfert-like spectra, including polarized Seyfert 1 lines) and hard X-ray (similar luminosities to radio quiet QSOs) emissions suggest that 3 or 4 are dominated bolometrically by an AGN (Arp 220 is the only clear exception; see AGN *vs* Starburst "scorecard" in Sanders 1999 for more detail). ULIRGs, like quasars, show morphological features of strong interactions.

3 The Need for Suzaku

It is clear that the nuclei of ULIRGs are very heavily obscured. Thus observations at UV, optical, near-infrared and even far-infrared wavelengths may not penetrate to the nucleus. High resolution ($\ll$ 1 arc sec), high frequency radio observations can penetrate high columns (depending on the ionization fraction) and are an excellent probe of whether an AGN is present. However, the bolometric luminosity in the radio band is totally insignificant, so radio observations can never prove that accretion onto a SMBH is the dominant energetic process (especially given the much lower spatial resolution of the *IRAS* and other far-infrared data). We are left with hard X-rays. While the ratio $\log[L_{2-10\ \mathrm{keV}}/L_{\mathrm{IR}}]$ is small (from -1 to -4) in nearby ULIRGs (e.g., Teng, Wilson, Veilleux, et al. 2005, ApJ, 633, 644), this ratio is not very much smaller than that found in radio-quiet QSOs (-1, -3). Moreover absorption may be a factor even at these energies. If the absorbing column exceeds $\sim 1 \times 10^{24}$ cm^{-2}, or Thomson depth $\tau_T \gtrsim 1$, the primary continuum emission is suppressed significantly by absorption and Compton down-scattering. Thus observations at $\gtrsim$ 20 keV are best to detect Compton-thick AGNs. The unprecedented sensitivity of Suzaku at $\sim 15-70$ keV and $\gtrsim$ 100 keV ($\gtrsim 2$ $-$ 10x better than *Beppo*SAX-PDS and RXTE-PCA/HEXTE) is ideally suited for this task.

4 The Sample

The five nearest and brightest ULIRGs in the *IRAS* Bright Galaxy Survey are Arp 220, Mrk 273, UGC 05101, Mrk 231, and F05189-2524 (Sanders et al. 1988). These are also by far the best studied ULIRGs. Arp 220 will be observed by Suzaku as part of the SWG campaign, so it is not included in our sample. Mrk 231 is also excluded from our sample since recent XMM-Newton + *Beppo*SAX observations by Braito et al. (2004, A&A, 420, 79) have already revealed a highly absorbed ($N_H \sim 2 \times 10^{24}$ cm^{-2}), high luminosity ($L_{2-10\mathrm{keV}} \sim 5-20 \times 10^{43}$ erg s^{-1}) QSO component in this object. Here we propose to conduct similar hard X-ray observations of Mrk 273 and F05189-2524. UGC 05101 is not part of our program because it is $\sim$ 5x and 23x fainter at $2-10$ keV than Mrk 273 and F05189-2524, respectively.

Name	cz (km s^{-1})	log L_{IR} ($L_\odot$)	$f_{25\mu m}/f_{60\mu m}$	log M_{H_2} ($M_\odot$)	Spectral Type	$F_{2-10\ \mathrm{keV}}$ (10^{-13} cgs)	$F_{60-200\ \mathrm{keV}}$ (10^{-13} cgs)
Mrk 273	11,332	12.10	0.10 (cool)	10.2	S2	8.3	<0.97
F05189-2524	12,801	12.10	0.25 (warm)	10.3	S2/S1	37.	149 (2.7 σ)

Both objects show strong signs of on-going galaxy interactions: Mrk 273 is in the early phase of a merger where the nuclei are separated by 680 pc, F05189-2524 is a unresolved late merger surrounded by tidal debris (e.g., Veilleux et al. 2002). Both are optically classified as a Seyfert 2 (Veilleux et al. 1999a). Near-infrared spectroscopy of F05189-2524 reveals the presence of an obscured BLR at Paα, while a [Si VI] 1.96 μm feature, a strong indicator of AGN activity, is detected in Mrk 273 (Veilleux et al. 1999b). Mid-infrared spectroscopy with ISO and SST suggests the presence of a powerful, possibly dominant AGN in both systems (Genzel et al. 1998; Veilleux et al. 2006, in prep.). Evidence for AGN activity in Mrk 273 is also present at radio wavelengths: its radio flux falls above the radio-to-FIR correlation of starbursts and a bright AGN-like radio core is detected on VLBA scale in this object (Lonsdale et al. 1993, ApJ, 405, L9).

Both targets have been studied at $\lesssim$ 10 keV with *CXO* and XMM-Newton (Ptak et al. 2003; Imanishi & Terashima 2004, AJ, 127, 758). Their spectra are remarkably similar: their soft ($0.5-2$ keV) X-ray emission is best explained with a MEKAL plasma with $kT \sim 0.4-1.3$ keV and their hard (2 - 10 keV) X-ray emission presents weak (Mrk 273) or absent (F05189-2524) Fe Kα emission and a flat ($\Gamma \sim 1$) power-law continuum. While the unusual slope of the hard X-ray continuum can be explained by invoking reflection from high-N_H neutral material, the weakness of Fe Kα is difficult to reconcile with this picture. A similar problem was encountered for Mrk 231 (e.g., Maloney & Reynolds 2000, ApJ, 545, L23) and solved by invoking emission scattered off of an ionized medium (Gallagher et al. 2002, ApJ, 569, 655; Braito et al. 2004). In the scattering-dominated model of Braito et al., the Fe emission line in Mrk 231 is produced by transmission through the $N_H \sim 10^{24}$ cm^{-2} screen and is diluted by the scattered component. Could this scenario also apply to Mrk 273 and F05189-2524? The *CXO*/XMM data on these two objects are not of high enough quality at > 6 keV to answer this question. The marginal (2.66 σ) *Beppo*SAX detection of F05189-2524 at 15-136 keV by Deluit & Courvoisier (2003, A&A, 399, 77) is tantalizing but needs to be confirmed. And the CGRO/OSSE ($50-100$ keV and $100-200$ keV) upper limits on Mrk 273 derived by Dermer et al. (1997, ApJ, 484, L121) are not stringent enough to rule out the possibility of a deeply embedded, energetically significant AGN in this object (an published analysis of INTEGRAL data obtained by Dermer and Veilleux on this object arrives at similar conclusions).

5 Goals of Present Proposal

Our main objective is to determine the contribution of the starburst and AGN to the total energy output of Mrk 273 and F05189-2524. We will use three complementary approaches to answer this question:

(i) *Emission at 10 – 60 keV.* Our main approach will rely on the exceptional sensitivity of Suzaku at $\sim 10-60$ keV, *i.e.* the spectral region covered by HXD-PIN. Starburst emission is generally too cool to mimic a power law spectrum above 3 keV, and the expected high-energy emission from X-ray binaries in the starburst can easily be accounted for using the soft ($\lesssim 2$ keV) X-ray emission as a gauge of the starburst strength. The remaining hard X-ray emission may come from an AGN seen either directly through a large absorbing column or reflected/scattered off of neutral or ionized material near the AGN (e.g., Mrk 231). The individual contribution of the direct and indirect components will be derived from fits to the broad-band (HXD + XIS) shape of the $\gtrsim 2$ keV continuum and the strength of the Fe Kα line and Fe K edge at 6-8 keV (which will be nicely sampled with XIS). If transmitted AGN emission is detected, the flux of this emission will be combined with the column of absorbing material derived from the fits to calculate the intrinsic unobstructed X-ray luminosity of the AGN. This luminosity will then be compared with that of classic QSOs of similar bolometric luminosity to estimate the contribution of the buried QSO to the total energy output of the ULIRG. The X-ray column will be compared with estimates from molecular gas studies and our medium-size Cycle 1 Spitzer survey of ULIRGs and PG QSOs (Veilleux et al. 2006, in prep.).

(ii.) *Hard X-ray Variability.* The detection of time-variable high-energy radiation from ULIRGs would prove the existence of AGNs in these systems. The Suzaku data will allow us to probe within light-hours of the central black hole, if present. First, the $2-10$ keV portion of our time-averaged spectrum will be compared with the *CXO* spectra of Ptak et al. (2003) to look for long-term (4-6 yrs) variability. Next, the Suzaku data will be examined for intra-day variability. Significant short-term variability (a decrease of $\sim 45\%$ in approximately 6 hours) was detected at energies above 2 keV in the *CXO* data of Mrk 231 (Gallagher et al. 2002). The amplitude and timescale of these variations were key ingredients in the interpretation of the 2-10 keV continuum in Mrk 231 as being mostly AGN emission scattered off of a highly ionized medium in the immediate vicinity of the AGN. The 2-10 keV luminosity in this object is therefore a direct measure of the intrinsic AGN luminosity, modulo the scattering fraction and N_H for the scattered component. Similar arguments could be used for Mrk 273 and F05189-2524.

(iii.) *Emission at very high energies.* Compton scattering opacity dominates photoelectric absorption at photon energies $\gtrsim 10$ keV, but the Klein-Nishina decline in the Compton cross section above ~ 100 keV makes the escape of higher-energy photons more probable. Very high energy observations with the GSO detectors may therefore provide the best means for detecting deeply buried AGNs. Detection at these energies depends largely on the cut-off energy of the AGN power-law continuum. Risaliti (2002, A&A, 386, 379) finds that the high-energy exponential cut-off at $E \sim 100-300$ keV is not an ubiquitous property of Seyfert galaxies: in $\sim 30\%$ of the objects the power-law continuum does not drop off at energies beyond 300 keV or more. Given the current lack of information on ULIRGs at these very high energies, the detection of > 100 keV emission from any of these two objects - or even an interesting upper limit on their > 100 keV flux - would have important implications on our understanding of the central engine in ULIRGs in general. Note, however, that the detectability of this high-energy tail will depend critically on the background estimation systematics (see §6 below).

We also plan to compare our Suzaku data with the SWG data on Arp 220 (once they are published or available from the archive) and the published *Beppo*SAX data of Mrk 231 to test, albeit with admittedly poor statistics, the predictions of the evolutionary scenario of Sanders et al. (1988): e.g., decreasing starburst/AGN ratio and N_H as the merger proceeds and the optical QSO emerges from its dusty cocoon.

This program addresses one of NASA's goals to understand the "Structure and Evolution of the Universe."

6 Feasibility

• **Detectability.** In the absence of reliable > 10 keV X-ray fluxes for both objects, we have used the best-fitting model for the XMM + *Beppo*SAX (76 ksec) spectrum of Mrk 231 from Braito et al. (2004) as a template for Mrk 273

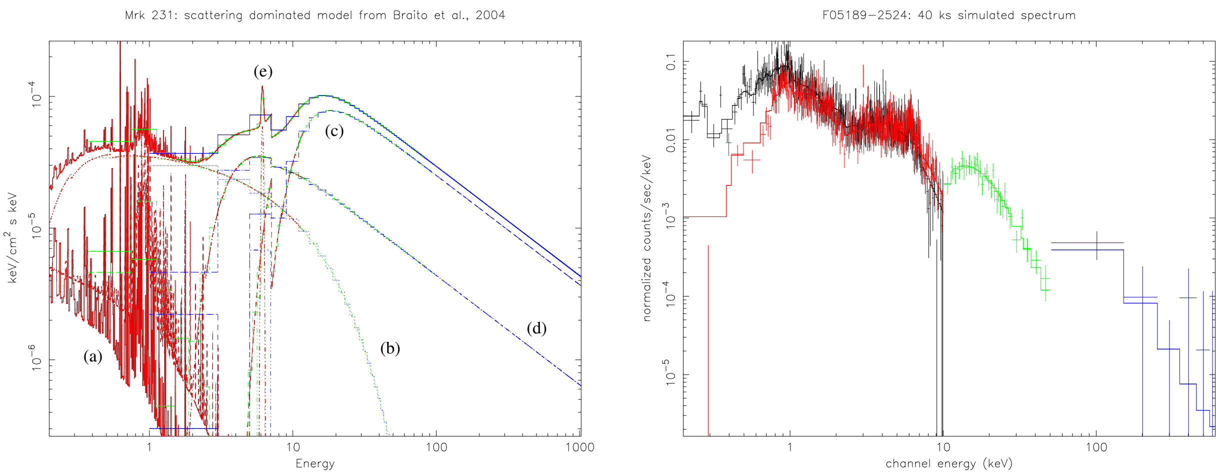

Figure 1: **Left:** Mrk 231 template. This is the best-fitting scattering-dominated model for the observed XMM + *Beppo*SAX (76 ksec) spectrum of Mrk 231 (Braito et al. 2004). It is the sum of (a) two MEKAL plasmas with kT = 0.35 and 0.91 keV, associated with the starburst, (b) a slightly absorbed ($N_H = 1.7 \times 10^{20}$ cm^{-2}) cutoff power law model of the form $E^{-\Gamma}\exp^{-h\nu/kT}$ with photon index $\Gamma \sim 1.1$ and cutoff energy $kT \sim 10$ keV, representing the high-mass X-ray binaries, (c) a highly absorbed ($N_H = 2 \times 10^{24}$ cm^{-2}) power law component with $\Gamma \sim 1.8$, representing the intrinsic AGN emisison transmitted through the Compton-thick screen (following Risaliti 2002, no high-energy cutoff is assumed), (d) an absorbed ($N_H = 1.2 \times 10^{23}$ cm^{-2}) power law having the same photon index as the transmitted component, representing the scattered AGN emission; and (e) a Gaussian line at $E \sim 6.4$ keV. The intrinsic $2-10$ keV luminosity of the AGN powering Mrk 231 is $\sim 4.5 \times 10^{43}$ erg s^{-1}, or about 0.3% of the infrared luminosity of this object. **Right:** Simulated 40 ksec Suzaku spectrum of F05189-2524 using the Mrk 231 template scaled up by 4.7x to match the 2-10 keV flux of F05189-2524. The nominal background was subtracted from this spectrum. The XIS data are shown for both the FI and BI CCDs. The December release of the XIS matrices was used for these calculations.

and F05189-2524 (see Fig. 1). The Mrk 231 template was properly scaled to reproduce the $2-10$ keV flux of each object. The count rate is thus (observed count rate for Mrk 231) $\times$ $f_{2-10\ \mathrm{keV}}$(galaxy)/$f_{2-10\ \mathrm{keV}}$(Mrk 231), where $f_{2-10\ \mathrm{keV}}$(Mrk 231) = 7.8×10^{-13} erg s^{-1} cm^{-2} (Ptak et al. 2003). The 60-200 keV flux of the F05189-2524 simulated spectrum is consistent to within a factor ~ 2 with the 2.7 σ *Beppo*SAX flux of Deluit & Courvoisier (2003). The total counts above 10 keV expected from a 80 ksec integration on Mrk 273 and a 40 ksec integration on F05189-2524 are $\sim$ 2900 cts and 4600 cts, respectively (these are medians from 10 simulations). The XIS counts are 3176 (BI) and 2576 (FI) for Mrk 273, and 6344 (BI) and 5236 (FI) for F05189-2524. In both objects, it will be possible to distinguish a buried or scattering-dominated AGN spectrum from that of a starburst, and detect the high-energy tail at > 100 keV, if present (Risaliti 2002), assuming nominal HXD background. However, we find that a +5% systematic error in the GSO background would prevent us from detecting this high-energy tail in both objects.

To further quantify the limits of the proposed Suzaku observations, we ran simulations where the strength of the intrinsic $\Gamma \sim 1.8$ AGN emission or the absorbing column of material in front of this AGN were changed from the canonical values of the properly scaled Mrk 231 template. When fixing N_H to 2×10^{24} cm^{-2}, the canonical value, we find that we are able to reduce the strength of the intrinsic AGN emission by a factor $\sim$ 12x (30x) for Mrk 273 (F05189-2524) before the object is undetected with PIN (10-50 keV) [assuming nominal background]. If, on the other hand, we fix the strength of the intrinsic AGN emission to the canonical value (scaled to reproduce the appropriate 2-10 keV flux) and vary N_H, we find that N_H can reach values of up to ~ 25 (75) $\times$ 10^{24} cm^{-2} before Mrk 273 (F05189-2524) is undetected with PIN (10-50 keV). At these extremely large N_H values, the 10-50 keV counts are dominated by the scattered component rather than the transmitted component. In summary, non-detections at 10-50 keV would provide very interesting constraints on the properties of the AGNs buried in these objects.

• **Contamination at high energies.** We have examined the hard X-ray source catalogs of RXTE-ASM, INTEGRAL, and Swift to determine if contamination by other sources within the field of view of the instruments is an issue for our observations. We find no other hard X-ray sources within a radius of 50′ ($E \lesssim 100$ keV) and $\sim 5.5^\circ$ ($E \gtrsim 100$ keV).