Measuring the Accreting Stellar and Intermediate Mass Black Hole Populations in the Galaxy and Local Group

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Measuring the Accreting Stellar and Intermediate Mass Black Hole Populations in the Galaxy and Local Group

The population of stellar black holes (SBHs) in the Galaxy and galaxies generally is poorly known in both number and distribution. SBHs are the fossil record of the massive stars in galaxy evolution and may have produced some (if not all) of the intermediate mass ($\gtrsim 100 M_\odot$) black holes (IMBHs) and, in turn, the central supermassive black holes (SMBHs) in galactic nuclei. For the first time, a Galaxy-wide census of accreting black holes, and their more readily recognizable tracer population, accreting neutron stars (NSs), can be measured. The key questions are:

1. What are the distributions and numbers of accretion-powered SBHs (vs. NSs) in the Galaxy and IMBHs in the Local Group?
2. Are ultra-luminous X-ray sources (ULXs) in nearby galaxies accreting IMBHs?
3. How do accreting SBHs vs. NSs produce jets, and are isolated SBHs or IMBHs in giant molecular clouds detectable by their Bondi accretion?

Tracing Stellar to Supermassive Black Holes

It is increasingly clear that black holes are fundamental to the lives of galaxies and the energetics of the Universe. While the Big Picture is dominated by the overwhelming role that supermassive black holes (SMBHs) play in the formation and feedback on growth of central bulges in galaxies, it is likely that the SMBHS are built in part by their stellar black hole (SBH) building blocks. The growth to SMBHs almost certainly includes mergers of SBHs in dense clusters (Portegies Zwart et al 2006) that may produce intermediate mass BHs (IMBHs), with masses $\sim 100 - 1000\ M_\odot$. These can augment the mergers in galactic nuclei to build up SMBHs. Likewise, the SBH population itself is partly driven by the neutron star (NS) population in galaxies and, particularly, in dense stellar clusters: NS-NS mergers to SBHs are then common, and produce short Gamma-ray bursts (Grindlay, Portegies Zwart and McMillan 2006)). The cascade of dependencies on lower mass compact objects as building blocks likely ends there, since accretion induced collapse to form NSs is less likely than SNIa's for accreting (or merging) white dwarfs.

Tracing the hierarchical growth of SBHs to SMBHs can be initiated by the populations of SBH and IMBH systems that are themselves revealed when they accrete from binary companions. X-ray binaries, both with low mass and high mass donors (LMXBs and HMXBs, respectively), are then the markers for black hole seeds and evolution in galaxies. But the very accretion processes that make them visible render them very much fainter $\gtrsim$99% of the time: accretion *instabilities* in their accretion disks shutoff the flow for either longterm deep quiescence or chaotic but usually short duty cycle transient outbursts. Thus the study of black hole demographics within galaxies demands the wide-field view and quasi-continuous monitoring that a hard X-ray imaging sky survey can provide as well as study.

These same new, more sensitive, survey capabilities can also probe what could be the last reservoir of BHs and possibly IMBHs in the Galaxy: those which must be undergoing Bondi accretion from Giant Molecular Clouds (GMCs), without binary companions, to be revealed as hard X-ray sources. With initial $\lesssim$20″ source positions and followup sensitive soft-medium X-ray and IR imaging ($\lesssim$0.2″) and spectroscopy, background AGN and binary companion can be eliminated for the most promising candidates. These may include IMBHs postulated to be in the galactic halo as remnant cores from sub-halo mergers (Volonteri and Perna 2005).

What we now know

Over 20 accretion-powered SBHs in binary X-ray sources are confirmed in the Galaxy by dynamical mass measurements of radial velocities of their secondary companions (Remillard and McClintock 2006). These SBHs have all been discovered as relatively luminous ($L_x \gtrsim 10^{36}$ erg s^{-1}) and bright ($\gtrsim$100mCrab) sources. All but the original SBH prototype, Cyg X-1, are transients (though with differing duty cycles) and have been discovered at rates of $\sim 0.5 - 1$/y ever since the bright prototype, A0620-00, was discovered (Elvis et al 1975). Most of these have had only 1-3 transient outbursts in the ∼35 year history of moderately (in)complete sky coverage, so their typical recurrence time is probably ∼20y. Another 20 sources, with similar X-ray properties (see below) and recurrence times are also probably SBHs though some (despite the absence of thermonuclear bursts, only possible on the solid surfaces of NSs) could be accreting NS-LMXBs.

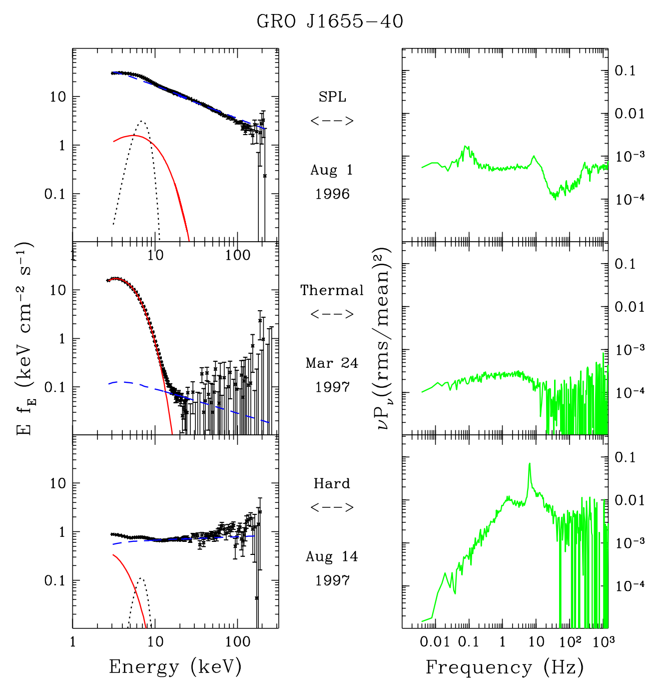

Fig. 1.— *Spectral states (left) and corresponding power density spectra (right) for the three states (steep power law, thermal and hard) of the SBH GROJ1655-40 (from Remillard and McClintock 2006).*

The galactic SBHs have relatively distinct X-ray spectral components, a soft thermal part associated with the accretion disk and one or more harder components which can extend to $\gtrsim$100 keV and whose origin is still controversial. Variations in these spectral components also correlate with short timescale variability properties and presence or absence of quasi periodic oscillations (QPOs). The low frequency QPOs, with frequencies generally 0.1 - 30Hz, correlate strongly with spectral state (Fig. 1) and can reach ∼20% rms power values, generally increasing with energy (up to the typically ∼20 keV limits imposed by medium energy observations.

These spectral-temporal properties are generally distinct from those for comparably luminous accreting NSs. The SBH systems are also strikingly correlated in their X-ray spectral states with well defined transitions in the X-ray spectral hardness vs. intensity diagram (see Fig. 2), when crossing the "jet line", to production of non-thermal radio emitting jets, revealed by their power law spectra and spatially resolved emission. This striking jet transition is marked by timing and spectral changes which appear to scale with BH mass, and radio:X-ray coupling may in fact scale over 7 orders of magnitude to apply to AGN (Falcke, Kording and Markoff 2004). Compact jets also found in the low hard state with synchrotron spectra and turnover frequencies in the near-IR (Corbel and Fender 2002) are reminiscent of the self-absorbed jets considered (Blandford and Konigl 1979) for flat-spectrum AGNs.

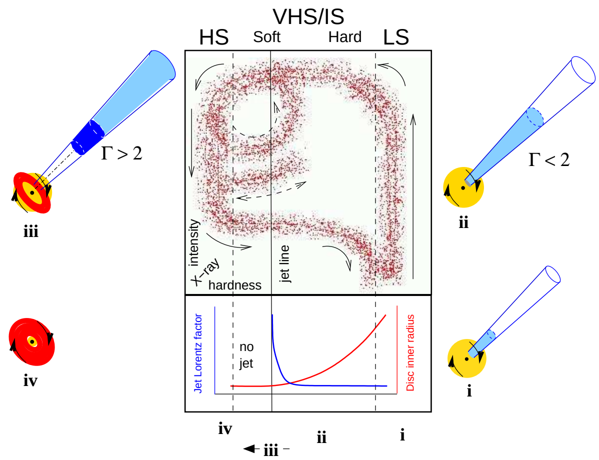

Fig. 2.— *Hardness (ratio hard/soft flux) vs. intensity diagram, increasing upwards and to right, for observed behaviour of SBHs which produce radio and non-thermal jets when crossing the "jet line" (from Fender, Belloni and Gallo 2004).*

Our knowledge of the spatial distribution of SBHs is limited by low statistics but nevertheless points to a disk and Bulge distribution. The long-recognized excess of luminous LMXBs (both NS and SBHs) in an "extended" (∼5°) Bulge distribution likely is connected to the radial distribution of much fainter ($L_x \sim 10^{31-33}$ erg s^{-1}) sources discovered initially with deep Chandra pointings (Muno et al 2003) and now traced to extend to much larger ($\gtrsim$4°) radii (Hong et al 2009). Although these sources likely are dominated by the more numerous accreting magnetic white dwarfs (CVs), a significant fraction are probably quiescent NS and SBH-LMXBs. There are no ULX sources, defined here as $L_x \gtrsim 10^{40}$ erg s^{-1}, in the Galaxy and thus candidate IMBHs, though SS433 and possibly Cyg X-3 are contenders if beaming corrections are included.

The largest source of confusion in the SBH population is the much larger population of NSs in LMXBs in their low luminosity (quiescent) states. These qLMXBs, undergoing minimal accretion in accordance with long term instability cycles, show hard PL spectra similar to SBH-LMXBs in their Hard state. This non-thermal spectral form for NS-qLMXBs is particularly dominant for accreting millisecond pulsars, which can be recognized by their coherent pulsations when in outburst. Their QPO power spectra are also separable (showing strong twin peak QPOs) from SBH systems, so that temporal analysis is needed to isolate the NS from SBH population. This distinction is possible in wide-field hard X-ray imaging survey data for moderately bright (∼10-100mCrab) sources and QPOs are readily detected in bright ($\lesssim$300 mCrab) sources even during scanning observations.

What is needed to disentangle the NS, SBH and IMBH Populations?
Given the "language" of accreting SBHs (Figs. 1 and 2), and the background "sea" of faint sources, which must include untold numbers of quiescent SBH-LMXBs (and NS-LMXBs), a sensitive hard X-ray imaging, spectroscopic and timing survey is needed to unravel the source populations. In order to recognize transients with a range of duty cycles and durations, wide-field (full sky) coverage is needed on $\lesssim$3h timescales. An energy band extending to at least 100 keV can allow a complete characterization of the hard component, and lower energy limit of ∼5keV ensures that the presence of the soft thermal component (cf. Fig. 1) can be established and its parameters measured. The primary discovery channel, hard X-ray imaging, must have $\lesssim 5'$ spatial resolution to disentangle $\gtrsim$30mCrab sources in the crowded central Galactic Bulge and it must locate sources (when bright) to $\lesssim$5-20$''$ to enable optical/IR (OIR) identifications. It should be able to respond to outbursts which may last only ∼1-2days (e.g. the peculiar hard X-ray "nova" CI-Cam (Belloni et al 1999) and conduct prompt OIR imaging and spectroscopy to directly identify the systems. And it should have high time resolution to distinguish the unique signatures of SBHs vs. NSs. These include the characteristic power spectra and QPOs of SBHs (Fig. 1) and sensitivity to X-ray bursts, and/or millisecond vs. longer period pulsations that immediately identify NSs accreting in LMXB or HMXB systems. Finally, to be able to detect ULX sources with $L_x \sim 10^{40}$ erg s^{-1}in Local Group galaxies at ∼3-4 Mpc distances requires sensitivities ∼0.5 - 1mCrab in the 20-100 keV band. This is comparable to that needed to detect SBHs in low-hard states or undergoing faint transient outbursts at $L_x \sim 5 \times 10^{34}$erg s^{-1}in the galactic center region.

In order to identify, and further characterize SBHs and IMBHs (detected as ULXs), the survey is further required to conduct higher sensitivity (narrow-field, focusing) imaging and spectroscopy at 0.1 - 10 keV to measure their low energy absorption column (NH) to guide simultaneous OIR imaging and spectroscopy for source identification in obscured or crowded fields. The final OIR imaging and spectroscopy must be conducted with $\lesssim 0.2''$ resolution for secure identifications.

And finally, to isolate NSs from the SBH sample, photon event timing is required with $\lesssim$0.1msec absolute timing to detect either coherent pulsations or kHz QPOs. For sufficiently faint sources, NS vs. SBH distinction may only be possible with the followup pointings of a sensitive soft-medium energy X-ray telescope (and OIR telescope) that are needed in any case for source identification.

Science from a SBH/IMBH survey that could EXIST

With a dedicated hard X-ray imaging survey, significantly more sensitive and thus able to speed up detections of SBHs (and NSs, and all other sources...) as compared to current wide-field galactic plane surveys with Swift/BAT or INTEGRAL/IBIS (Kuulkers et al 2007), an exciting range of new science on demographics (and physics) of black holes in the Galaxy and Local Group becomes possible. Here we itemize some of the results that would likely arise from a survey with the instrument complement and mission currently in final phases of an Astrophysics Strategic Mission Concept (ASMC) Study: the newly-designed (for ASMC) Energetic X-ray Imaging Survey Telescope, **EXIST**, see Appendix.

SBH Spectral States Survey:

Every 3h (2 orbits), all known SBHs and all possible candidates with F(5-100keV) $\gtrsim$4mCrab, corresponding to $L_x \gtrsim 3 \times 10^{35}$ erg s^{-1}at the Galactic Center, would have its spectrum measured and approximate spectral state (Figs. 1 and 2) established. Sources found to have very high states, with PL index ∼2.5, are likely SBH candidates, as may be those with steep/soft + hard components. Only Hard state (PLs with index $\lesssim$2) are possible NS systems, which are identified either through the detection of pulsations/X-ray bursts or by the combination of spectral and timing parameters. At low luminosities, SBH and NS transients can be very similar and only distinguished if they show state transitions or X-ray bursts. *By continuous coverage with fine imaging and spectroscopy for 2y, and then nearly continuous (daily) coverage for 3y more, the full SBH catalog for the Galaxy will be assembled.*

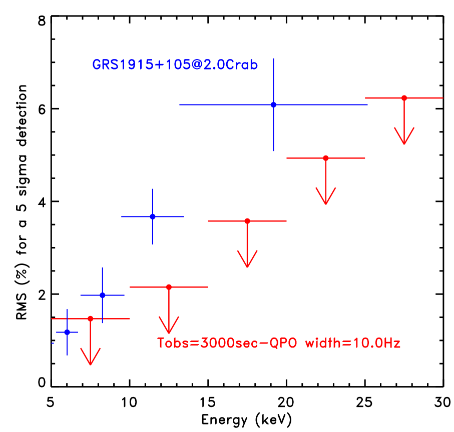

Fig. 3.— *Sensitivity of EXIST (red) for a 3000s pointing or ∼10 orbits of scanning coverage on the SBH GRS1915+105 and its 67Hz QPO, with ∼10Hz width. The rms vs. energy actually observed with RXTE (Morgan et al 1997) are the blue points.*

SBH Temporal States Survey:

The same survey observations just described will yield the first truly continuous sampling of timing properties of SBHs, which are intimately connected to the spectral variations. For the brightest sources, low- frequencies QPOs can be detected, but also the elusive high-frequency QPOs, probably directly connected to the Keplerian motion of matter close to the black-hole can be detected (as shown in Fig. 3 for GRS 1915+105). NS QPOs are known to show a very different timing phenomenology and they will be easily identified in the sample. The S/N for broader QPOs in SBHs can be improved by co-adding power spectra from several orbits or from the pointings that will occur for GRB and bright transient followups during the scanning survey mission phase (2y) and followup pointed mission phase (3y).

First continuous SBH vs. NS Survey:
A key goal for the Galactic and Local Group BH survey is to detect and characterize transients as plausible SBH or IMBH candidates. For the Galaxy, the number of new SBH transients expected over 5y is at least 5-10 (conservatively), and more likely $\gtrsim$100. The lower value is straight extrapolation of the coverage of "classical" X-ray astronomy for the past 40y with luminous transients ($\gtrsim$1 Crab at peak; with typical decay times of 30d) occurring at rates of $\sim$0.5 - 1/yr. However EXIST would be at least 10X more sensitive and, equally important, has significantly larger duty cycle to be on source for short-timescale outbursts. EXIST would measure the (PL?) distribution of outburst amplitudes and durations of SBHs, which will constrain the total SBH population. In the past decade, accreting millisecond pulsars have been discovered and associated with relatively weak NS transients. The survey capabilities of EXIST will offer the unique combination of discovery of any outburst from new systems and the detection of pulsations by covering their full outburst.

First continuous ULX/IMBH Survey in Local Group:
Both the 2y scanning and then 3y pointing mission phases of EXIST would allow the first continuous survey for outbursts of known IMBHs in the Local Group. The EXIST sensitivity is sufficient to detect the known ULX sources and candidate IMBHs, within M33 and M82, over 0.9mo and 2.8mo integration times for their quiescent flux values of $\sim$0.8 and 0.4mCrab (2-10 keV) corresponding to $L_x \sim 9 \times 10^{39}$ erg s^{-1}for both. The ULX in Holmberg IX, with quiescent flux $\sim$0.2mCrab and $L_x \sim 3 \times 10^{39}$erg s^{-1}could be detected on a 9mo timescale. Flaring outbursts from any of these will be detected on shorter timescales. These sources have only been ever observed sporadically with pointed soft X-ray telescopes (ROSAT, Chandra and XMM) so little is known about their long term variability of flaring states.

First full-sky Survey for IMBHs and SBHs in GMCs:
Finally, the long-discussed possibility (e.g. Grindlay 1978, Agol and Kamionkowski 2002) that isolated IMBHs could be detected undergoing Bondi accretion from giant molecular clouds (GMCs) in the galactic plane could be tested. For spherical accretion onto an IMBH of mass M moving at velocity V through a GMC with particle density n (cm^{-3}) of Hydrogen with proton mass m_p, the Bondi accretion rate is $\dot{M} = 4\pi n m_p\, (GM)^2/V^3$. For a halo remnant IMBH with velocity V = 100 km/s and mass $M = 10^3\ M_\odot$ and GMC (core) gas density n = 10^5 cm^{-3}, this would then give an accretion luminosity, assuming a (conservative) accretion efficiency $\epsilon = 10^{-4}$, $L_x \sim 5 \times 10^{35}\ \epsilon_{-4}\ M_3^2/V_{100}^3$, where subscripts denote the assumed scaling values. With a 2y full sky scanning survey sensitivity of Fx(5-100keV) $\sim$0.06mCrab = 3 x 10^{-12}erg cm^{-2} s^{-1}, the corresponding distance such a IMBH-GMC could be detected is d $\sim$40 kpc, so the entire Galaxy disk (and beyond) and GMC distribution could be surveyed. Given the likely small number of IMBHs in the Galaxy halo ($\lesssim 10^3$?) and small filling factor, no detections are likely. However for SBHs, with $M = 10 M_\odot$ and V = 10km/s, the M^2/V^3 factor increases by a factor of 10 and so the survey for isolated SBHs in dense clouds becomes very feasible even for accretion efficiencies 1-2 orders of magnitude smaller. Thus the population of isolated stellar mass BHs passing through spiral arms and GMCs or dense clouds in the

disk should be detectable as a population of hard sources with low energy cutoffs, and for which IR imaging and spectra would not reveal them to be LMXBs or background AGN.

Appendix: Brief Description of EXIST:
EXIST (see http://exist.gsfc.nasa.gov/) is a LEO mission (600km, i =15/deg) with a primary wide-field survey High Energy Telescope (HET) employing a 4.5m^2 imaging (0.6mm pixels) Cd-Zn-Te (CZT) detector array sensitive over the 5-600 keV band. This views the sky through a 7m^2 coded mask 2m above the detector plane to achieve $2'$ imaging resolution and $\lesssim 20''$ (90% confidence radii) source positions within a 90° X 70° FoV. Two narrow-field imaging telescopes and spectrometers are included to conduct the required prompt optical-IR and soft X-ray source identifications and followup studies. A 1.1m telescope optical-IR telescope (IRT), with simultaneous optical (0.3 - 0.9μm) and IR (0.9 - 2.3μ) imaging (0.15$''$ pixels) and spectroscopy (R = 30 or 3000), achieves high sensitivity (AB = 24 in 100s, enabled by cooling (-30C) the primary/secondary mirror to achieve zodiacal light-limited backgrounds. The Soft X-ray Imager (SXI), proposed to be contributed by Italy, is significantly more sensitive than the XRT on Swift. The proposed 5y mission would spend the first 2y continuously scanning the sky (full sky every 2 orbits, or 3h), interrupted by Gamma-ray Bursts (GRBs) $\sim$2X per day which are imaged in real time ($\sim$10-20sec) by HET to then slew the spacecraft to point the HET, SXI and IRT on the GRB position for source imaging identification and prompt redshift measurement. After a 2y scanning survey (HET and SXI), EXIST would be in pointed mode for the next 3y to followup with high sensitivity observations of survey sources. The HET would still cover $\gtrsim$90% of the sky each day. During the scanning mission, the full sky is imaged to 5σ sensitivity F(5-100keV) $\sim$4mCrab per 2 orbits, with total equivalent on-axis exposure $\sim$8.4min on any source. For comparison with INTEGRAL/IBIS, which achieves F(20-60 keV) $\sim$7 mCrab in 3.5h of on-axis exposure for a *single* 10° FoV (Kuulkers et al 2007), EXIST would reach the same sensivity *over the full-sky* every 8 orbits, or $\sim$0.5day of elapsed (clock) time.

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