10 Active Galactic Nuclei

W. Niel Brandt, Scott Anderson, David Ballantyne, Aaron Barth, Robert Brunner, George Chartas, Willem de Vries, Mike Eracleous, Rob Gibson, Richard Green, Mark Lacy, Paulina Lira, Jeffrey Newman, Gordon Richards, Donald Schneider, Ohad Shemmer, Howard Smith, Michael Strauss, Daniel Vanden Berk

GTR: This starts out sounding like LSST is a fiat-accompli as it starts of being data-centric. Rather, I think that the first paragraph or two should be science-centric.

GTR: Maybe something like: Although the numbers of known quasars have grown considerably in the past decade, there is a vast amount of discovery space that can be probed by quasars. For example, the average separation between SDSS spectroscopic quasars is 100 Mpc (check number), which limits the kinds of clustering analyses that be done with quasars. In addition, the dynamic range in luminosity of current samples is generally not large enough to break the ever-present luminosity-redshift degeneracy inherent to all flux-limited samples. Current surveys are also limited in terms of absolute numbers of rare classes. As such, much larger quasar samples that probe to high-redshift over a large dynamic range will significantly improve our knowledge of over an array of topics that can be probed by quasars [be specific instead of general]? At the same time, the design parameters required to create quasar samples of sufficient size and dynamic range in luminosity and redshift will allow hitherto impossible investigations.

GTR: If we did this, this whole section would need to be re-arranged a bit so that all of the science is at the beginning and the data-related text follows. Right now there is some interleaving.

The LSST active galactic nuclei (AGN) survey will produce a high-purity sample of at least ten million well-defined optically-selected AGNs (??). Utilizing the large sky coverage, depth, the six filters extending to 1µm, and the valuable temporal information of LSST, this AGN survey will dwarf the largest current AGN samples by more than an order of magnitude. This dataset will provide the basis of a number of investigations of fundamental scientific questions posed by the AGN phenomenon, as we describe in this chapter. The merit of this sample does not lie solely in its enormous size; it will also span more than a factor of one thousand in luminosity at a given redshift, and will allow detection of AGN out to redshifts of approximately seven, spanning ∼95% of the age of the Universe.

The goal of AGN statistical studies is to define the changing demographics and accretion history of supermassive black holes (SMBHs) with cosmic time, and to relate these to the formation and evolution of galaxies. These results are tightly coupled with the evolution of radiation backgrounds, particularly the ultraviolet ionizing background and diffuse X-ray background, and the co-evolution of SMBHs and their host galaxies. The LSST AGN sample will be used by itself and in conjunction with surveys from other energy bands to produce a measurement of
the AGN luminosity function and its evolution with cosmic time (??) and the evolution of the bolometric accretion luminosity density.

AGN clustering is a reflection of the dark matter halos in which these objects are embedded. LSST’s enormous dynamic range in luminosity and redshift will put important constraints on models for the relationship between AGN and the dark matter distribution, as described in ??.

AGN are an inherently broad-band phenomenon, with emission from the highest-energy gammarays to long-wavelength radio probing different aspects of the physics of the central engine. LSST will overlap surveys carried out in a broad range of wavelengths, allowing studies of a large number of multi-wavelength phenomena (??).

Each region of the LSST sky will receive roughly 1000 visits over the decade-long survey, about 200 in each band, allowing variability to be explored on timescales from minutes to a decade (??). Optical variability will be used to identify AGN (??) and also to explore central engine physics for AGN identified by variability-based and other metrics. The enormous sample will enable the discovery of extremely rare events, such as transient fueling events from stars tidally disrupted in the gravitational field of the central SMBH (??). There will be a large number of multiply-lensed AGN (?? and ??); microlensing from stars in the lensing galaxies can probe the structure of the central engine.

GTR: A technical suggestion is to make all of the file names adhere to some convention. Eg., var.tex should be agn_var.tex, etc.

GTR: Another generic comment is that the references are skewed somewhat to “self” references. Adding a few references to people currently outside the collaboration would have a positive political impact.

10.1 AGN Selection and Census

Scott Anderson, Richard Green, Donald Schneider, Ohad Shemmer, Daniel Vanden Berk

10.1.1 AGN Selection

There are three principal ways in which AGN will be identified in LSST data: from their colors in the LSST six-band filter system, from their variability, and from matches with data at other wavelengths.

Color Selection

Unobscured AGN with a broad range of redshifts can be isolated in well-defined regions of optical–near-IR multicolor space (??). At low redshifts \( z \lesssim 2.5 \), quasars are blue in \( u - g \) and \( g - r \), the ultraviolet excess sources of (??) and (??), and are well-separated from stars. At higher redshift, the Lyman alpha forest (starting at 1216\( \AA \)) and the Lyman limit (at 912\( \AA \)) marches to ever longer wavelengths, making objects successively redder.
10.1 AGN Selection and Census

To zeroth order, the continuum of an unobscured quasar longward of Lyα is a power-law, and thus its colors are independent of redshift. However, the broad strong emission lines of high equivalent width modulate the colors as a function of redshift, allowing photometric redshifts to be determined with surprising fidelity (\textsuperscript{25}), especially once the Lyα forest enters the filter set. \textsuperscript{25} shows the colors of quasars and stars as convolved with the LSST filters. The quasar spectra are from the SDSS first data release, (\textsuperscript{26}), and the stars were drawn from the atlas of ?\textsuperscript{27}. The u-band exposures are crucial for selection of low-redshift (z < 2) AGN; observations in this filter allow one to distinguish between AGN and stars (in particular white dwarfs and A and B stars). High-redshift AGN will be easily distinguished; the y filter should allow quasars with redshifts of 7 to be selected (compare SDSS, whose filter set ends with the z band; it has discovered quasars with redshift up to 6.4, ?\textsuperscript{28}). As with SDSS, most of the sample contamination is in the range 2.5 < z < 3, where quasar colors overlap the stellar locus in most projections. GTR: It would be interesting to plot u − g vs. g − r color-coded by z − y to see if that will allow some separation at z ∼ 2.5 (similarly at z ∼ 3.5) for g − r vs. r − i. It is also difficult to select quasars at z ∼ 3.5, where Lyman-limit systems cause quasars to be invisible in u and g but quasars have similar colors to hot stars at longer wavelengths. However, the lack of proper motion, and especially variability, will allow quasars to be efficiently separated from stars in these redshift ranges, as we describe below.

There are several complications with these color determinations:

- The LSST (unlike the SDSS) will not measure a given area of sky through the various filters simultaneously. GTR: I don’t see how this is an issue. The mean colors of the quasars will be exactly what they would have been had all of the data been taken simultaneously. Because of variability, the colors will therefore not exactly reflect the colors of the object at a given moment in time. Given the rapid cadence of LSST, a given area of sky may be observed in more than one filter on timescales of less than a week, this is unlikely to be much of a problem for all but the most violently variable objects. GTR: I don’t follow this last sentence at all.

- More importantly, for low-luminosity systems, the colors of AGN will be contaminated by the colors of their hosts. Simulated LSST images (e.g., ?\textsuperscript{29}) will help to characterize this effect in LSST fields. Variability will allow such objects to be selected, as will photometric measurements of unresolved point sources in the centers of galaxies.

- The majority of quasars used in ?\textsuperscript{25} are not significantly reddened. However, there is great interest in the reddened population (\textsuperscript{30}). While the most heavily obscured (“type 2”) quasars will not be recognized as AGNs using LSST alone, millions of type 2 quasars will be detected by LSST in their host galaxies and narrow line regions. These objects can be recognized as AGNs by their infrared, radio, or X-ray emission, as we describe below.

Selection by Lack of Proper Motion

Lack of proper motion will further distinguish faint quasars from stars. The 3σ upper limit on proper motion for the full 10 years of the LSST survey is intended to be 3 milli-arcsec at r ∼ 24, and five times better at r = 21. The stringent upper limit on proper motions will essentially
Figure 10.1: Color-color plots of known quasars from SDSS (colored dots) and stars (black dots) in the LSST photometric system. The quasars are color coded by redshift according to the color key, and for clarity, the dot size is inversely proportional to the expected surface density as a function of redshift. Since there is no $y$ filter in the SDSS system, a random Gaussian color offset has been added to the $z - y$ color according to the width of the stellar locus in the $i - z$ color. GTR: I'm confused here. Is the $z$ data faked (and meaningless)? Why not use real (simulated) $z$-band colors? The quasar colors become degenerate with those of F stars at redshifts between about 2.5 and 3. See ?? for redshifts above 5.
eliminate the relatively nearby L and T dwarfs as contaminants of the very high-redshift quasar candidate lists, and also remove many of the white dwarfs and subdwarfs.

It is illustrative to consider the case of contamination of the color selection by white dwarfs, which can overlap as ultraviolet excess objects at low redshift, and (for cooler white dwarfs) as objects with similar colors to $3.2 < z < 4.0$ quasars. For each quasar redshift, we use the white dwarf color-absolute magnitude diagram to estimate the white dwarf properties most closely matched to the quasar energy distribution. The typical distances of these objects at $r = 24$ place these contaminants in the thick disk population.

<table>
<thead>
<tr>
<th>Quasar $z$</th>
<th>WD $M_V$ for $Qs (V-I)$</th>
<th>WD $T_{\text{eff}}$</th>
<th>Distance (pc) at $r = 24$</th>
<th>3$\sigma$ limit $v_{\text{tan}}$ (km s$^{-1}$)</th>
<th>Fraction excluded</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>13.7</td>
<td>6500</td>
<td>1260</td>
<td>17.6</td>
<td>77%</td>
</tr>
<tr>
<td>3.6</td>
<td>15.7</td>
<td>4500</td>
<td>660</td>
<td>9.4</td>
<td>88%</td>
</tr>
<tr>
<td>4.0</td>
<td>16.5</td>
<td>3500</td>
<td>500</td>
<td>7.1</td>
<td>92%</td>
</tr>
</tbody>
</table>

The width of the distribution of the thick disk component of the velocity dispersion is $\sim 60$ km s$^{-1}$ (\%). With a Gaussian form for the velocity dispersion and the 3$\sigma$ upper limits for proper motion quoted above, we compute the fraction of the thick disk white dwarfs excluded.

If we consider a halo subdwarf at the main sequence turn-off detected at $r = 24$, the distance is some 50 kpc. Even then, the proper motion upper limit rejects half of the tangential velocity distribution of the outer halo, with its dispersion of $\sim 130$ km/s.

The conclusion is therefore that moderate to low-temperature white dwarfs will be effectively screened. The space distributions of hotter white dwarfs and main sequence stars earlier than K spectral type place the vast majority of them in the brighter magnitude range typical of the current SDSS samples. They would therefore not be expected to be significant contaminants at these faint magnitudes. An increasing fraction of the halo subdwarfs will remain as contaminants as the LSST survey limits are approached. The decrease in surface density of very distant halo main sequence stars will counteract the increasing fraction of the population with apparently zero proper motion from the relaxing of tangential velocity limits toward the faintest survey magnitudes.

**Selection by Variability**

Variability will add a powerful dimension to AGN selection by the LSST, since AGN vary in brightness at optical and ultraviolet wavelengths with a red-noise power spectrum. has suggested that the efficiency of AGN selection by variability may be comparable to the color selection efficiency. The amplitude of AGN variability depends upon rest-frame variability timescale, wavelength, luminosity, and possibly redshift (e.g., \%). We use the parameterized description of AGN variability from the SDSS extrapolated to fainter apparent magnitudes, to estimate the fraction of AGN in the LSST that may be detected as significantly variable. Given the depth of individual LSST exposures, we calculate the magnitude difference at which only 1% of the
non-variable stars will be flagged as variable candidates due to measurement uncertainty, first assuming two measurement epochs separated by a month, and also assuming 12 measurement epochs spanning a year in total.

The probability that the single-band rms magnitude difference of an AGN will exceed this value, and will therefore be flagged as a variable candidate, depends upon redshift (as it determines rest wavelength and rest-frame variability timescale), luminosity, observed temporal baseline, and the number of observing epochs. Here we follow the model of ?, and show the results in ??.

Even with only two epochs separated by 30 days, a large fraction of AGN will be detected as variable objects. The fraction of AGN detected depends strongly on absolute magnitude at each redshift; intervening Lyman series absorption shortward of the 1216Å Lyman α emission line also affects the detection probability. After 12 epochs with a total temporal baseline of 360 days, nearly all of the AGN to a limiting apparent magnitude of 24 will be detected as variable. The detection fraction will increase as the number of epochs increases, and the use of all six bands will improve the detection fraction even further. Ultimately, LSST will provide ∼ 200 epochs for each AGN candidate in each band, thus increasing the detection fraction as well as increasing the limiting magnitude.

The LSST temporal information will be especially useful for selecting low-luminosity AGN which would otherwise be swamped by their hosts, as well as radio-loud AGN, since these will have larger variability amplitudes and shorter variability timescales (e.g., ?). Variability will also allow selection of AGN that cannot otherwise be selected due to their confusion with stars of similar color.
Selection by Combination with Multiwavelength Surveys

Cross-correlation of LSST imaging with multi-mission, multiwavelength surveys will also contribute to the AGN census by allowing selection of sources that cannot easily be identified as AGN by color selection, lack of proper motion, or variability, including optically obscured quasars. With its faint limiting magnitude, LSST will also enable serendipitous detections of AGN in existing deep surveys. For example, cross-correlations of LSST images with Chandra or XMM-Newton observations can reveal obscured AGN that are not easily identifiable via standard optical techniques. In addition, X-ray sources that have no LSST counterparts in any band may be candidates of $z > 7$ quasars. Many high-redshift AGN may also be detected by matching LSST images with future surveys such as VISTA, JDEM, EXIST, and JANUS. See ?? for further discussion.

GTR: I don’t think that EXIST and JANUS are well-known enough to merit reference here. And what’s the status of JDEM? Need to be clear here that only small areas will match LSST depth and only wide surveys will provide significant numbers. This part is a bit tricky as basically the argument for LSST is essentially that there are no other data sets to match it to.

GTR: Add photo-z section here? This won’t take me too long, but I need to get the simulated data from Xiaohui first.

10.1.2 Expected Number of AGN

The growth in the benchmark sizes of individual quasar samples is impressive over the past several decades, starting at $N \sim 10^{0-1}$ (e.g., ??), but growing rapidly to $10^{2}$ (e.g., ??), and then to $N \sim 10^{3}$ (e.g., ?) by the 1990s. The most recent decade has seen the continuation of an exponential expansion in the number of quasars identified in homogeneously selected samples, extending to moderate depth: for example, 25,000 color-selected quasars to $b_J < 20.85$ are included in the final 2dF QSO Redshift Survey catalog (??), and SDSS is approaching $N \sim 10^{5}$ spectroscopic quasars (mostly with $i < 19.1$) (??), and $N \sim 10^{6}$ photometrically-selected quasars to $i < 21.3$ (??). LSST will provide a major leap forward in quasar sample size, plausibly identifying over $10^{7}$ quasars to beyond $m \sim 24$ through the variety of selection approaches we’ve just outlined.

An estimate of LSST’s coverage of the quasar redshift-magnitude plane is given in ??. GTR: This should be redone with the Hopkins, Richards, & Hernquist 2007 QLF. The Croom QLF doesn’t extend to high enough redshift. HRH07 is the best compilation to date that spans the necessary range in L and z. I’ll work on this. The only issue is that HRH is somewhat more pessimistic than HRH. So, it might make sense to include a high-z prediction from each. In either case, I’d change the redshift spacing to 0.5 and extend to at least z of 6. The numbers of quasars in the various bins were calculated using the latest quasar luminosity function from the 2dF-SDSS Luminous Red Galaxy and Quasar Survey data (??), extrapolated to low luminosities. LSST should detect nearly nine million AGN with $M_g \leq -20$ with $g \leq 24.5$ and redshifts below 3.5; this number rises to over 12 million for $g \leq 26.5$.

The Chandra Deep Fields show a surface density of order 7000 AGN per deg$^2$ (??, e.g.,), which, when extrapolated to the 20,000 deg$^2$ of LSST, implies a total count of over $10^8$ AGN, an
order of magnitude larger than the optical AGN luminosity function would predict. This may be thought of as a reasonable upper limit to the number of AGN that LSST might find, as it includes optically obscured objects and may include objects of intrinsically lower luminosity than we’ve assumed, and may also point to errors in our (admittedly blind) extrapolation of the measured luminosity function. Indeed, this gives us motivation to *measure* the luminosity function, as we discuss below in ??.

One of the most important discoveries of LSST is expected to be the detection of many AGN at the end of the cosmic ‘Dark Ages’. The $y$-band filter will permit selection of quasars out to $z \sim 7$ and down to moderate AGN luminosities ($\approx 10^{45}$ ergs s$^{-1}$) in surprisingly large numbers, despite their anticipated rarity. For example, the high-redshift quasar luminosity function extrapolated to the depths and areal coverage of the full LSST survey predicts $\sim 200 - 1000$ quasars at $6.5 < z < 7.5$ (??); such quasars should be detected as $z$-band dropouts and will be followed up spectroscopically from the ground and with JWST. This will exceed the current number of the most distant SDSS quasars at $5.7 < z < 6.4$ by an order of magnitude (e.g., ??). The LSST census of $z \sim 7$ quasars will place tighter constraints on the cosmic environment at the end of the reionization epoch and on the SMBH accretion history in the Universe.

### 10.2 AGN Luminosity Function

*Scott Anderson, Richard Green, Donald Schneider, Ohad Shemmer*

The census of AGN through cosmic time, tracing the evolution of supermassive black holes, may be quantified via the AGN luminosity function (hereafter, LF), as well as closely related empirical measures such as the log $N$ – log $S$ curve. The LF impacts studies of the ionizing background radiation, the X-ray background, quasar lensing, and constrains a variety of parameters in...
Figure 10.3: **Left:** LSST $z - y$ vs. $y$ color-magnitude diagram, showing the expected allowable region for $z \sim 7$ quasar candidates (cyan). The region limits are defined by the 5 $\sigma$ $y$-magnitude detection limits, and 2 $\sigma$ $z$-magnitude detection limits, as a function of the number of co-added 15 s exposures. An object is considered a $z \sim 7$ candidate if it is detected at the $> 5 \sigma$ level in the $y$-band, and does not exceed the $z$ band $2 \sigma$ detection limit. The $y$-magnitude detection limits reached in a given number of exposures are shown by red dots, and labeled by the number of exposures. The $y$-magnitudes and $z - y$ color limits are shown for simulated $z = 7$ quasars at three different 5100 Å continuum luminosities. The open stars show the minimum $z - y$ color limits required for a single 15 s exposure, and the ends of the arrows show the limits for 400 exposures (the full extent of survey). A quasar at $z = 7$ with an optical luminosity of $10^{45}$ ergs s$^{-1}$ can be detected in about 50 exposures, while quasars with optical luminosities exceeding $10^{46}$ ergs s$^{-1}$ can be detected in a single exposure. The expected $z - y$ colors of stars (green) and $z < 6$ quasars (blue), based on results from the SDSS, are shown for comparison. The minimum $z - y$ colors lie well above the star and low-redshift quasar color distributions. **Right:** Track of a quasar with an optical luminosity of $10^{46}$ ergs s$^{-1}$ on the $z - y$ vs. $i - z$ color-color diagram. Note that such quasars can be easily separated from the loci of stars (black) and lower redshift quasars (colored). GTR: I don’t follow either this plot or the text in the least. (And I’ve now read through it 5 times.)
physical models for the evolution of AGNs, including black hole masses, accretion rates and Eddington ratios, the fraction of galaxies (perhaps most GTR: MOST galaxies do NOT go through an AGN phase. Most massive galaxies do.) that undergo an AGN phase and the lifetime of this phase, and cosmic down-sizing (e.g., ??). The variety and sensitivity of LSST-enabled AGN-selection metrics will result in a high-quality, representative AGN sample required for detailed LF studies. In particular, the large area, depth, and dynamic range of LSST form a superb basis to study the populous faint end of the LF at moderate to high redshifts.

The exponential growth in quasar survey sample size in the decades since their discovery (??), is—aside from pencil beam surveys covering small regions of the sky—not nearly as dramatic at “ultrafaint” ($m > 22.5$) magnitudes that sample the low-luminosity end of the LF. For example, the pioneering photographic studies of Koo, Kron, and collaborators (e.g., ?) which extend to $B < 22.6$ over 0.3 deg$^2$, are still often quoted in current studies as among the handful of reliable points in LF studies of the faint AGN population. Significant expansions in areal coverage from a few $m \sim 22.5$ modern CCD-based surveys are underway (e.g., 3.9 deg$^2$ in the SDSS faint quasar survey of ??).

Yet there are strong motivations in LF studies to explore much fainter than the break in the number counts distribution, and this sparsely sampled ultrafaint regime is one where LSST is poised to have significant impact on LF studies. Only ultrafaint ($m > 22.5$) surveys can probe the populous, faint end of the AGN LF, especially at moderate to high-redshifts. For example, an AGN with absolute magnitude $M = -23$, i.e., a high space density object from the faint end of the luminosity function, will have apparent magnitude $m > 22.5$ at $z > 2.1$.

?? shows our current understanding of the optical AGN counts as a function of magnitude. Among the most reliable points at ultrafaint magnitudes well beyond $m > 22.5$ are those of the COMBO-17 survey, although there are a handful of other smaller area optical surveys using a variety of selection criteria that give similar results at least for AGNs out to $z < 2.1$. This figure suggests that LSST will discover of order 500 photometric AGNs/deg$^2$ to $m < 24.5$ and $z < 2.1$, in rough agreement with the numbers we found above. To the extent that we can identify AGNs from the coadded data below the single-visit limits, we should be able to find appreciably more objects.

Given the very large numbers of AGNs that LSST will find, a bin of a few tenths in redshift covering a decade in luminosity will include thousands of AGNs over much of the redshift range, allowing statistical errors to be negligible, and systematic errors (due to errors in photometric redshifts, bolometric corrections, or selection efficiency) will dominate our measurements. Of course the efficacy of any AGN census for establishing the LF is not measured merely by the numbers of objects sampled. Survey depth, sky coverage, dynamic range, completeness, contamination, redshift range, wavelength selection biases/limitations, are all additional key elements. An example recent survey embodying many of these as attributes is the 2SLAQ survey of 8700 AGNs over 190 deg$^2$, which extends to $g < 21.85$ (?). But the dynamic range, redshift range, depth and sky coverage of the LSST AGN sample will be much more impressive.

The impact of LSST depth and dynamic range in magnitude and redshift for ultrafaint AGN LF studies may be seen in the context of current LF models. One popular form for the LF considered in many recent studies is a double power law with characteristic break at luminosity $L_*$. The LF shape might evolve with redshift in either luminosity, density, or both (e.g., ?).
10.2 AGN Luminosity Function

Figure 10.4: A summary of our current understanding of the numbers of AGNs per square degree of sky brighter than a given apparent magnitude, from ?. The ultrafaint points are from the COMBO-17 survey (5-pointed stars; ?) and HST based surveys (circles and squares; ?). Shown for broad comparison are: brighter 2SLAQ points (upside-down triangles; ?); a simple extrapolation of 2SLAQ points to ultrafaint magnitudes (solid line); and the ? compilation (small triangles), which incorporates many earlier quasar surveys. The data show \( \sim 500 \) AGNs deg\(^{-2}\) to \( m < 24.5 \) and \( z < 2.1 \). The LSST AGN surveys will extend both fainter and across a much wider redshift range, suggesting a sample of at least \( \sim 10^7 \) AGNs. GTR: quality of this figure is poor. Don’t use compressed JPEGs.

For several decades, studies tended to favor pure luminosity evolution models, but more recent studies from various wavebands (some extending quite deep in small areas, such as the X-ray studies of ??) sometimes found markedly disparate evolutionary rates, depending on their energy selection wavebands. Preliminary indications are that the slope of the AGN luminosity function varies considerably from \( z = 2 \) to \( z = 6 \) (?). In reconciling multiple survey results from various wavebands, there has been a recent resurgence in combined luminosity/density evolution models, which incorporate downsizing scenarios for the LF. These are well represented by the bolometric LF studies of ?, in which the peak of the AGN space density is argued to occur at increasing redshifts for more luminous AGNs.

?? (adapted from figure 8 of ?) shows a realization of one of these models: it adopts the usual double power-law shape, but allows for a break luminosity \( L_\ast \) that evolves with redshift as shown by the solid line. Superposed are dotted red curves representative of the faint limits of the 2SLAQ and the SDSS photometric surveys (?). These surveys don’t probe significantly beyond the break luminosity over for redshift much larger than 2. range is enormous. The bright limit is indicated by the cyan curve, and the faint limit in a single visit probes to the break luminosity to \( z = 4.5 \), and to \( z = 5.5 \) in the coadded images, even in this model in which the break luminosity decreases rapidly at high redshift.
With the large number of objects in the sample, the dominant uncertainties in LF studies will be systematics, such as the contamination of the sample by non-AGNs, completeness, and uncertainties associated with photometric redshifts. Internal comparison of LSST color-, variability-, and proper motion-selected AGN surveys will limit contamination and enhance completeness, while comparison with deep Chandra X-ray and Spitzer mid-IR data will allow the selection effects to be quantified. There is clearly a need as well for spectroscopic follow-up of a modest subset of the full LSST sample to further quantify the contamination of the sample from non-AGN.

GTR: There is nothing in here about the meaning of the QLF slopes in terms of the new paradigm set forth by DiMatteo, Hopkins, etc. In particular the bright end slope telling us about the properties of the host galaxies (merger rates, etc.) and the faint end slope telling us about the lifetimes. I’ll work on adding something about this.

Figure 10.5: Depth and redshift coverage of large, optical surveys, compared to a representation of the LF of $\gamma$. The evolution of the break luminosity $L_*$ with redshift is shown by the solid black curve (adapted from Hopkins et al.). The corresponding sensitivity of two current large quasar surveys is depicted by the dotted red curves (2SLAQ and SDSS photometric surveys). The depth of the LSST AGN survey will permit a much more sensitive measure of the break luminosity evolution at intermediate to high-redshifts, encompassing (in a single sample) $0 < z < 4.5$ (magenta curve reflecting LSST single-visit depth), and perhaps $0 < z < 5.5$ (lower cyan curve reflecting final, stacked LSST depth). The cyan curve to the upper left reflects the bright limit of LSST (in a single visit).
10.3 The Clustering of Active Galactic Nuclei

Michael Strauss, Robert Brunner, Jeffrey Newman

The evolution of galaxies is intimately tied with the growth and energy output from the supermassive black holes which lie in the centers of galaxies. The observed correlation between black hole masses and the velocity dispersion and stellar mass of galaxy bulges seen at low redshift, and the theoretical modeling that suggests that feedback from AGN regulates star formation, tell us that AGN play a key role in galaxy evolution. An important piece of the puzzle comes from understanding the physical nature of the galaxies that host AGN and the conditions that cause infall and growth of the black hole. GTR: These sentences may be better in the introduction as they apply to the QLF science as well. Then could shorten this to one summary sentence with a cross-reference to the intro. One important diagnostic in this regard is the spatial clustering of the AGN.

The luminous parts of galaxies of course represent only a small fraction of the clustered mass density of the universe, and there is no guarantee that the clustering apparent from the matter that we see matches that of the underlying dark matter perfectly (??). A common hypothesis, which is predicted, e.g., in so-called threshold bias models in which galaxies form only in regions of high density contrast in the dark matter, is that the fractional density contrast \( \delta(r) \equiv \frac{\rho(r) - \langle \rho \rangle}{\langle \rho \rangle} \) as measured for galaxies is proportional to that of the dark matter:

\[
\delta_{\text{galaxies}} = b \delta_{\text{dark matter}}.
\]

Here where the bias factor \( b \) may be a function of the smoothing scale on which \( \rho \) is measured. This simple relation is often referred to as a linear bias model (as opposed to models which include higher-order terms or scatter around this simple deterministic relation; see also the discussion of halo occupation distribution models in ?? and ??).

In threshold bias models, the bias factor \( b \) is directly related to the value of the threshold. To put it another way, one can determine the characteristic mass of the dark matter halos associated with a given sample of galaxies directly from a measurement of their clustering. GTR: Emphasize this sentence? It is clear, whereas the previous stuff isn't unless you are already familiar with this kind of thing. The sense of it is that the higher the halo mass associated with the galaxy population in question, the higher the bias, and therefore the stronger the expected clustering.

In practice, this GTR: This what.? is quantified by measuring the correlation function \( \xi(r) \) (or its Fourier Transform, the power spectrum) of the galaxy sample, as described in ??, and comparing it with that of the underlying dark matter as predicted from linear theory (on large scales) or N-body simulations (on smaller, non-linear scales). The linear bias model states

\[
\xi_{\text{galaxies}} = b^2 \xi_{\text{dark matter}},
\]

where again \( b \) may be a function of \( r \). Our current cosmological model is precise enough to allow a detailed prediction for \( \xi_{\text{dark matter}} \) to be made.

The galaxy correlation function at low redshift has been measured precisely, using samples of hundreds of thousands of galaxies (from the redshift survey of the SDSS; see e.g., ??), allowing quite accurate determination of the bias as a function of scale for various subsets of galaxies.
Chapter 10: Active Galactic Nuclei

However, AGN are rarer, and the measurements are not as accurate. GTR: Mention mean high-z separation for an example. The enormous AGN samples selectable from LSST data (??) will cover a very large range of luminosity at each redshift, allowing the clustering, and thus bias and host galaxy halo mass, to be determined over a large range of cosmic epoch and black hole accretion rate.

While gravitational instability causes the contrast, and therefore the clustering of dark matter to grow monotonically with time, observations of galaxies as a function of redshift shows their clustering strength measured in comoving units to be essentially independent of redshift (albeit with increasingly larger error bars at higher redshift). This is roughly as expected, GTR: I’d say understood instead of expected. It was only “expected” a posteriori. if (for a given population of galaxies) the characteristic halo mass is independent of redshift. As one goes to higher redshift, and therefore further back in time, the amplitude of the underlying dark matter clustering decreases, meaning that this characteristic halo mass represents an ever-larger outlier from the density contrast distribution, and is therefore ever more biased. Quantifying this relation allows one to measure the characteristic halo mass of galaxies as a function of redshift. GTR: A plot like Figure 7 from Ouchi et al. (2004, ApJ, 611, 685) would be really useful here. Indeed it is surprising that that galaxy section doesn’t include it.

We would like to do the same for AGN, to determine the masses of those halos that host them. The observed correlation function of luminous quasars at all redshifts below $z \sim 3$ is very similar to that of luminous red ellipticals, suggesting that they live in similar mass halos, and perhaps that these quasars are hosted by these elliptical galaxies (e.g., ?, and references therein).

How does the clustering depend on AGN luminosity? The AGN luminosity depends on the mass of the central black hole, and the Eddington ratio. It has been suggested that the mass of the central black hole is correlated with that of its host halo (?); after all, these black holes are correlated with the mass of the spheroidal components of galaxies, and the masses of these spheroids are plausibly correlated with the mass of the halo, as modern Halo Occupation Distribution (HOD) models would suggest. Thus if most AGN are accreting at close to the Eddington limit (??), one might imagine a fairly significant correlation of clustering strength with luminosity. If, on the other hand, luminosity is driven more by a range of Eddington ratios, such luminosity dependence becomes quite weak (?). Models of black hole growth differ largely on questions of the duration of the accretion and the level and constancy of the Eddington ratio, thus measurements of the luminosity dependence of the clustering strength become particularly important.

Current samples, however, simply do not have the dynamic range in luminosity at any given redshift to allow this test to be done robustly. For example, the SDSS quasar sample (?) has a range of only about two magnitudes (a factor of less than 10 in luminosity) over most of its redshift range. Samples going deeper do exist over small areas of sky, but do not probe the large scales where the linear clustering is best measured. The current measurements of the luminosity dependence are poor: the data are consistent with no luminosity dependence at all (although there is a hint of an upturn for the highest luminosity decile, ?), but the error bars are large, the range of luminosities tested is small, and redshift and luminosity evolution are difficult to separate out.
The LSST will increase the dynamic range enormously over existing samples. At most redshifts, we will be able to select AGN with absolute magnitudes ranging from $-29$ to $-20$ (??), a factor of several thousand in luminosity, and the numbers of objects in moderate luminosity bins will certainly be large enough to measure the correlations with high significance. There must be a luminosity dependence to the clustering at some level if black hole masses are at all correlated with halo masses; this may only become apparent with samples of such large dynamic range.

At higher redshifts, ?? have found that the clustering length grows with redshift: $17 \pm 2 \, h^{-1}\text{Mpc at } z \sim 3.2$, and $23 \pm 3 \, h^{-1}\text{Mpc at } z \sim 4$; ?). This suggests both that the most luminous objects at these redshifts are accreting at close to the Eddington limit (and therefore their luminosities reflect their black hole masses), and the black hole masses are tightly coupled to their halo masses (?). Exploring these connections at lower luminosities is crucial, as has been emphasized by ?, where different models for AGN feeding can be distinguished by the luminosity dependence of clustering at $z > 3$. This is illustrated in ??, which shows the substantial dependence of the quasar bias and comoving clustering length on redshift and luminosity as predicted in various models. Most of the luminosity dependence, and the distinction between models, becomes apparent at $z > 3$, where existing data are very limited. An important exercise for the future is to make detailed predictions for the uncertainties in the LSST clustering measurement, limited as it will be to angular clustering because of the inaccuracies of the photometric redshifts.

From the measurement of quasar clustering, we get an estimate of the minimum mass of the halos hosting them. Given a cosmological model, the number density of halos of that mass can be predicted, and the ratio to the observed number density of quasars allows inference of the duty cycles of quasars. With existing data (?), this test gives uncertainties of an order of magnitude; with LSST, this can be done much more precisely and explored as a function of luminosity, thereby further constraining models of AGN growth.

The small-scale clustering of AGN can be studied in great detail with LSST; the coadded photometry will go deep enough to see host clusters, for example, to at least $z = 4$. This gives an independent test of bias relations as a function of redshift; given that the highest-redshift quasars are so strongly biased, they live in particularly massive halos, and therefore are likely to lie in regions in galaxy overdensity. These data will allow us to explore how quasars fit into the Halo Occupation Distribution picture as a function of luminosity and redshift (??). Indeed, the quasar-galaxy cross-correlation function can be measured to much higher precision than the auto-correlation function, simply because there are so many more galaxies in the sample (see the discussion in ??). As ? describe, the cross-correlation of quasars with either the general galaxy population or specific galaxy subsamples can be directly compared to the auto-correlation of that galaxy sample to place constraints on the quasar bias, its evolution with redshift and luminosity, and the quasar host halo mass at different cosmic epochs. GTR: I think that credit for this idea goes back to a Kauffmann paper. Also should reference Coil’s work.

LSST will also be able to resolve close companion galaxies to quasars, allowing us explore how mergers drive quasar activity. Finally, the stacked images will go to low enough surface brightness and have enough dynamic range to separate out quasar host galaxy light; an important exercise for the future is to quantify to what extent this will be doable as a function of luminosity and redshift.
Figure 10.6: The bias (top panels) and comoving clustering length (lower panels) of quasars in three models of quasar growth, for samples of various limiting magnitude. The LSST will be able to probe to limiting magnitudes of $m \sim 26$ reliably. Measured data points, entirely limited to $z < 2.5$, are shown as colored points with error bars. Note that the models are essentially entirely degenerate, with no luminosity dependence, in this redshift range; all the action is at $z > 3$. The three models are (left to right): an efficient feedback model (in which infall to the SMBH halts immediately after a quasar episode); a model in which SMBHs grow smoothly to $z = 2$; and a model in which black hole growth is tied to that of the dark matter halo to $z = 2$. GTR: Need to emphasize that these models are degenerate at high-z also at the SDSS flux limit. Only by probing to fainter limits AND high-z do we break the degeneracy. Figure from [7], with permission.
Finally, LSST will explore the nature of quasar pairs and the quasar correlation function on small (< 1Mpc) scales. It is known that quasars show an excess of pairs over what is expected given an extrapolation of the power-law from larger scales (??); this will be explored with exquisite statistics and over a wide range of luminosity with LSST. GTR: If I understand correctly, here I think that on small scales the question is whether quasars are ignited pre-merger or whether the probability of a merger increases with the local density of objects on small scale. With current data leaning towards the latter. Even projected pairs are tremendously useful; follow-up spectroscopy allows the environments (IGM, companion galaxies) and isotropy of the emission of the foreground object to be probed from their signature in the absorption spectra of the background object (??).

10.4 Multi-wavelength AGN Physics

Scott Anderson, David Ballantyne, Rob Gibson, Ohad Shemmer

GTR: This section is begging for a figure. Maybe like the ones that I have been making for Stripe 82, showing the relative depth of various surveys. As I mentioned above, the one thing that needs to be made clear here is that the need for LSST is, in part, because there are no good data sets in other wavelengths to match it to. You either get area or depth, but never both. Even to the single-epoch LSST depth.

AGN emit strongly across a very broad energy range, typically with prodigious luminosity spanning at least from the infrared through the X-ray, and sometimes extending to radio and/or gamma-ray energies as well. Although a power-law is often used to describe the broad optical-UV spectral energy distribution (SED) of AGNs, such a characterization is a marked oversimplification: quasars display a diversity of radiation emission and absorption mechanisms that add complexity to their SEDs, but also enable a more detailed understanding of their complicated and rich multi-region structure. Luminous radiation at different energies may arise from distinct regions and physical processes, and may dominate the observed emission for different AGN subclasses. Sometimes, specific wavebands outside the optical are more direct probes of the quasar bolometric luminosity, or more direct measures of conditions nearest the central engine. For example, dust-obscured quasars are more readily found and studied in the infrared, and some quasar central engines enshrouded by moderately thick columns of intrinsic absorbing gas are best-studied via hard X-rays.

Surveys at other wavelengths are thus essential companions to LSST optical studies to obtain fully reliable physical diagnostics for AGN, and to count and classify the wide range of observed AGN phenomena with minimal bias. Moreover, cross-correlations between the multi-epoch optical photometry of LSST AGN and overlapping contemporaneous multiwavelength survey data will provide unprecedented, time-dependent coverage of the AGN SED. Such time-dependent measures will provide a unique view of remarkable sources such as blazars, broad-absorption line (BAL) quasars, and perhaps new types of AGN that LSST will discover. LSST AGN studies will benefit from contemporaneous multiwavelength wide surveys such as VISTA, WISE, EXIST, and JANUS (???) and from existing wide surveys such as NVSS, 2MASS, COSMOS, GALEX, ROSAT, XMM-Newton, and Fermi [GTR: Add refs].
The depth and sky coverage provided by LSST are essential for characterizing and classifying optically-faint AGN that are bright in other wavebands, but that cannot be studied with shallower optical surveys such as the SDSS (?). Any sky areas—whether by design or by serendipity—in which past, present, or future deep multiwavelength surveys overlap with LSST sky coverage, will be promoted by LSST investigations to “optical plus multiwavelength Selected Areas.” LSST AGN with multiwavelength data available will have less selection bias than AGN selected by LSST optical colors alone (?), allowing large samples to be constructed that are representative of the overall AGN population.

For example, LSST imaging of the Chandra Deep Field South region in the “deep drilling” LSST mode (?) would enable one to study heavily obscured AGN in more detail and place tighter constraints on their properties. LSST studies of radio galaxies will similarly flourish via comparison of LSST optical data and both deep pencil-beam and wider-area radio surveys in the regions of overlapping sky coverage. The multiwavelength characteristics of LSST AGN will also highlight the most promising subset for spectroscopic follow-up. Such sources may include remarkable outliers, “borderline” sources in classification schemes, and interesting subtypes of AGN that are strongly distinguished by their unusual radio, infrared, optical-UV, and/or X-ray colors. Similarly, AGN that display dramatic photometric variability will make prime targets for followup spectroscopy and spectroscopic monitoring, as we describe further in ??.

### 10.4.1 Multiwavelength AGN Classification

GTR: This section is too X-ray centric. It would help to have an opening paragraph that explains that there are some types of AGNs that LSST won’t find (or, more accurately, will find, but won’t be able to identify as AGNs). Mention that X-ray and IR are important. *Then* can launch into X-ray (and IR) details.

Overlapping X-ray observations will be a valuable component of source-classification algorithms for LSST AGN; X-ray-to-optical flux ratios of AGN are roughly \( \approx 0.1 - 10 \) (e.g., ??). The ROSAT All-Sky Survey (?) and the XMM-Newton Slew Survey (?) will overlap the LSST survey region, giving shallow X-ray coverage to nearly all LSST AGN. GTR: This make is sound like all LSST AGN will be detected in the X-ray, which is clearly not the meaning here. But there are already \( \sim 10^2 \text{deg}^2 \) of sky covered with Chandra to a depth sufficient to detect \( 10^2 \text{AGN deg}^{-2} \) (e.g., ?), and of course this area will continue to expand. In addition, the X-ray SED slope (equivalently, the ratio between hard and soft X-rays) is an indicator of X-ray absorption, allowing one to distinguish between Type 1 and Type 2 AGN (e.g., ?). X-ray-bright sources may also be found with faint or undetectable LSST counterparts (see also ??); these sources are plausibly obscured AGN (e.g., ?), or perhaps very high-redshift (\( z > 7 \)) quasars.

Heavily obscured LSST AGN may also be identified by combining LSST optical colors with sub-millimeter surveys (e.g., ?), or mid-IR photometry from Spitzer (e.g., ?). There are of order \( 10^2 \text{deg}^2 \) of deep mid-IR imaging data from surveys like SWIRE (?); these surveys have AGN surface densities approaching \( 10^3 \text{deg}^{-2} \). Combining LSST data with these surveys and X-ray data may even be used to identify Compton thick AGNs, and mid-infrared photometry can also
10.4 Multi-wavelength AGN Physics

improve photometric redshift estimates over purely optical estimates. Cross-correlating mid–far-IR data, e.g., from Spitzer and Herschel GTR: reference needed. with LSST AGN will also improve our understanding of the starburst-AGN connection across cosmic time.

Radio survey data GTR: From where? of LSST AGN will allow us to distinguish between radio-loud and radio-quiet AGN, test the dependence of radio power on luminosity and redshift, and probe unification models. The combination of X-ray, radio, and LSST photometry may identify new blazars from their unusual location in X-ray-radio-optical multi-color/-wavelength diagrams (e.g., ??). Additional gamma-ray information from the Fermi Gamma-ray Space Telescope GTR: reference needed. will enable better understanding of how SMBHs accelerate immense jets of material to nearly the speed of light. Though detailed Fermi results are not yet publicly available at the time of writing, $\sim 10^{3-4}$ gamma-ray blazars are predicted to be selected and monitored at high energies (whole sky). Moreover, LSST may contribute significantly to Fermi blazar identifications: for example, LSST may discover transient/variable optical objects coincident with radio sources and inside Fermi persistent gamma-ray error circles, or transients/variables may be caught flaring contemporaneously in both LSST and Fermi. Blazars display dramatic SED changes, which are associated with the jet acceleration mechanism. LSST will provide optical light curve information on few day (or better) timescales for $10^{2-3}$ Fermi blazars (with $m > 17$) in the LSST sky region; Fermi’s lifetime will plausibly suffice to provide extraordinary contemporaneous blazar gamma-ray lightcurves extending down to intra-day time resolution, for high-energy comparison to corresponding LSST optical lightcurves of the full ensemble.

Multiwavelength data for the large census of LSST AGN will produce the largest inventory of AGN SEDs over a very wide wavelength range, allowing better constraints on accretion as well as reprocessing mechanisms. This large inventory may also enable identification of AGN candidates with atypical accretion properties; spectroscopic follow-up will provide verification and characterization of their physical properties. For example, the optical–X-ray spectral slope and its dependence on luminosity will be studied in greater detail across a broader luminosity and redshift range to improve characterization of the scatter about the overall trend of SED shapes (e.g., ??). Identification of outlier populations from this SED-luminosity dependence will require further scrutiny with other instruments to search for unusual sources with atypical SEDs, such as AGN that are intrinsically X-ray weak (e.g., ??).

10.4.2 Time-Dependent SEDs

GTR: This section is sort of awkward here. It should probably go somewhere else. At the very least another sentence or two could help provide a better segue. Also, the fact that it references only 2 Gibson papers is bound to make some people angry.

Augmenting LSST photometry with multiwavelength data will also enable unprecedented temporal investigations. Hundreds of repeat LSST observations in each band will reveal the extent to which the scatter in measured SED shapes can be attributed to near-IR–optical variability over observed time scales of days to a few years. For example, ?? have found that UV-to-X-ray flux ratios range over a factor of 100, perhaps due to intrinsic SED diversity, differential UV/X-ray variability (since the UV and X-ray observations were not contemporaneous), or a combination of both. Current attempts to obtain near-simultaneous snapshots of UV and X-ray SEDs
(e.g., with XMM-Newton or Swift) are limited in numbers, bandpasses, and sensitivity, but the multiwavelength surveys overlapping in time with the LSST project will provide accurate, contemporaneous SEDs for a large number of AGN. GTR: Not really, since other wavelengths probe other scales at the central engine. Thus, “simultaneous” measurements are not.

BAL outflows provide another example of the variety and power of LSST-enabled studies of SED variation. BAL outflows, and their AGN hosts, have been studied in the radio, infrared, optical-UV, and X-rays (e.g., ?, and references therein). Their SEDs reveal information about the structure and evolution of UV and X-ray absorbers in the central region of an AGN. LSST will monitor the light curves and colors of ~2000 BAL quasars identified in current (2009) catalogs, and (at least) thousands more will be identified in the LSST fields by SDSS–III and future surveys. This will enable other observatories to trigger follow-up observations based on dramatic changes in the absorption or emission of these sources, and will provide detailed light curves useful for studies of photoionization in BAL absorbers. Near-simultaneous, multiwavelength observations will also improve constraints on the shape and variation of absorbed SEDs.

10.5 AGN Variability

W. Niel Brandt, Willem de Vries, Paulina Lira, Howard Smith

GTR: This section *must* include a structure function figure.

One of the key characteristics of AGNs is that their emission is variable over time. In addition to aiding effective AGN selection (see ??), this time dependence offers a probe of the physics associated with the accretion process. While there is no model capable of explaining all aspects of AGN variability in a compelling manner, effects including accretion-disk instabilities, changes in accretion rate, the evolution of relativistic jets, and line-of-sight absorption changes have all been invoked to model the observed variability.

The characteristics of AGN variability are frequently used to constrain the origin of AGN emission (e.g. ??). AGN variability is observed to depend upon luminosity, wavelength, time scale, and the presence of strong radio jets. However, despite considerable efforts over last few decades, conflicting claims about correlations with physical properties exist. This is at least in part due to the fact that many early studies included at most only 50–300 objects and had a limited number of observation epochs (see ??).

Significant progress in the description of AGN variability has recently been made by employing SDSS data (??????). ? used two-epoch photometry for 25,000 spectroscopically confirmed quasars to constrain how quasar variability in the optical/UV regime depends upon rest-frame time scale (up to ≈ 2 years in the observed frame), luminosity, rest wavelength, redshift, and other properties. They found that accretion-disk instabilities are the most likely mechanism causing the majority of observed variability. ? and ? utilized SDSS and Palomar Observatory Sky Survey (POSS) measurements for 40,000 quasars spectroscopically confirmed by SDSS, and constrained quasar continuum variability on time scales of 10–50 yr in the observer’s frame. In the context of a shot-noise light-curve model, ? found evidence for multiple variability timescales in long-term variability measurements. Using SDSS repeat spectroscopic observations obtained
more than 50 days apart for 315 quasars which showed significant variations, demonstrated that the difference spectra are bluer than the ensemble quasar spectrum for rest-frame wavelengths shorter than 2500 Å with very little emission-line variability. The difference spectra in the rest-frame wavelength range 1300–6000 Å could be fit by a standard thermal accretion-disk model with a variable accretion rate. GTR: Other (more well known) references needed here. E.g., the Hubeny series.

However, these studies were limited in what they could study, given that each object in their sample was observed only twice. The LSST variability survey will be unrivaled in its combination of size (millions of AGNs, as we’ve seen), number of observation epochs, range of timescales probed (rest-frame minutes-to-years), multi-color coverage, and photometric accuracy. Relations between AGN variability properties and luminosity, redshift, rest-frame wavelength, time scale, color, radio-jet emission, and other properties will be defined with overwhelming statistics over a wide range of parameter space. Degeneracies between the potential controlling parameters of variability will be broken, enabling reliable determination of which parameters are truly fundamental. With appropriate spectroscopic follow-up, it will also be possible to relate AGN variability to emission-line and absorption-line properties, as well as physical parameters including black-hole mass and Eddington-normalized luminosity (e.g. ?). Both the observed luminosity and spectral variability of the optical/UV AGN continuum will used to test accretion and jet models.

The LSST AGN variability survey will also greatly improve our categorization of the range and kinds of AGN variability. Rare but physically revealing events, for example, will be detected in sufficient numbers for useful modeling. These are expected to include transient optical/UV obscuration events due to gas and dust moving temporarily into the line of sight (e.g. ???), strong intranight variability events (e.g. ??), and perhaps quasi-periodic oscillations. Notable events discovered by LSST will trigger rapid follow-up with other facilities, and LSST photometry will automatically synergize with many AGN monitoring efforts (e.g., wide-field X-ray and gamma-ray monitors; reverberation-mapping projects). AGN lifetimes, or at least the timescales over which they make accretion-state transitions, will also be constrained directly by looking for objects that either rise or drop strongly in flux (e.g. ?).

10.6 Transient Fueling Events: Temporary AGNs and Cataclysmic AGN Outbursts

Aaron Barth, W. Niel Brandt, Mike Eracleous, Mark Lacy

Strong transient outbursts from galactic nuclei can occur when a star, planet, or gas cloud is tidally disrupted and partially accreted by a central SMBH. The tidal field of a SMBH is sufficient to disrupt solar-type stars that approach within \( \sim 5 M_7^{2/3} \) Schwarzschild radii, where \( M_{SMBH} = M_7 \times 10^7 M_\odot \) (?). An optical flare lasting several months is expected when the star disintegrates outside the event horizon, i.e. for \( M_7 < 20 \). Transient variability may also arise during the inspiral and merger phases of binary SMBHs. LSST will be a premier facility for discovering and monitoring such transient SMBH phenomena, enabling and aiding studies across the electromagnetic spectrum as well as detections with gravitational waves.
10.6.1 Tidal Disruption Events by Supermassive Black Holes

The models of tidal disruptions predict optical emission from a hot optically thick accretion disk dominating the continuum and enhanced by line emission from unbound ejecta (??). The peak brightness can reach $M_R = -14$ to $-19$ mag approaching that of a supernova. The expected full sky rate of events down to a 24 mag threshold ($z \sim 0.3$) is $10^4 M_t^{3/2} \text{ yr}^{-1}$. Multi-epoch X-ray and UV observations have discovered about eight candidates for tidal-disruption events in the form of large-amplitude nuclear outbursts (e.g. ????). These events have large peak luminosities of $\approx 10^{43}$–$10^{45}$ erg s$^{-1}$, optical-to-X-ray spectral properties broadly consistent with those expected from tidal disruptions, and decay timescales of months. The inferred event rate per galaxy is $10^{-5}$–$10^{-4}$ yr$^{-1}$ (??), roughly consistent with the predicted rate for stellar tidal disruptions (e.g. ?). These X-ray and UV outbursts are theoretically expected and in some cases observed (??) to induce accompanying optical nuclear variability that will be detectable by LSST.

LSST will dramatically enlarge the sample of detected tidal-disruption events, thereby providing by far the best determination of their rate. ? have used the currently known UV/optical events to estimate rates, and predict that LSST should detect $\approx 6000$ tidal disruptions per year. With such a large sample, it will be possible to measure outburst rates as a function of redshift, host-galaxy type, and level of nuclear activity. This will allow assessment of the role that tidal disruptions play in setting the luminosity function of moderate-luminosity active galaxies (e.g. ?).

An interesting subset of tidal-disruption events involves the disruption of a white dwarf by a black hole of mass $< 10^5 M_\odot$ (e.g. ??). Detection of the prompt optical flash of such an event with the LSST would allow rapid followup spectroscopy to confirm the nature of the event through the composition of the debris. Such events are of particular interest because they can reveal the presence of moderately massive black holes in the nuclei of (presumably dwarf) galaxies. Black holes in this mass range are “pristine” examples of the seeds that grow to form the most massive black holes known today (see ?, and references therein). As such they provide strong constraints on models of hierarchical galaxy assembly and growth of their central black holes.

The tidal disruption events that have been discovered to date were mostly identified after they were largely over. However, LSST data processing will provide near-instant identification of transient events in general and new tidal disruptions in particular (??), so that intensive optical spectroscopic and multiwavelength follow-up studies will be possible while the events are in their early stages. Prompt and time-resolved optical spectroscopy, for example, will allow the gas motions from the tidally disrupted object to be traced and compared with computational simulations of such events (e.g. ?). Joint observations with LSST and X-ray missions such as the Black Hole Finder Probe (e.g. ?), JANUS, and eROSITA will allow the accreting gas to be studied over the broadest possible range of temperatures and will also constrain nonthermal processes such as Compton upscattering and shocks. LSST identifications of tidal disruptions will also complement LISA detections as these events are expected to create gravitational-wave outbursts (e.g. ?).
10.6.2 Inspirals of Binary Supermassive Black Holes

SMBH mergers are an expected component of models of galaxy evolution and SMBH growth. The correlation of the masses of the central SMBHs in galaxies today and the velocity dispersions of their bulges implies a close link between the build-up of mass in galaxies and the build-up of mass in their central SMBHs, a significant fraction of which happens as a result of mergers in many models (e.g. ??).

Several dual SMBH systems have already been found in the form of quasar pairs, but most have relatively wide (∼ 10 kpc) separations (?,?). At lower redshift, there are now several examples of dual AGN with ∼ kpc separation in merging galaxies, the best-known case being NGC 6240 (e.g. ?). True binary systems, in which the two SMBHs are tightly gravitationally bound to each other, have proved more difficult to find, and the single nearby example is a binary with 7 pc separation discovered in the radio with VLBI (?). Theory indicates that dynamical friction will cause the SMBHs in galaxy merger events to sink to the bottom of the common potential well formed at the end of the merger on a timescale of ∼ 10^7 yr. There they form a SMBH binary system with pc-scale separation, primarily by ejecting stars from the core of the galaxy (e.g. ?). These binary systems may be, however, resistant to further decay (?) until the separation reaches less than about 10^{-3} pc, when gravitational radiation becomes an effective mechanism for angular momentum loss (the “inspiral” phase).

The solution to the stalling of the binary separation at the parsec scale probably lies in gas. In the most-likely case of an unequal mass merger, an accretion disk around the primary SMBH can exert a torque on the secondary component, reducing its angular momentum over a period of ∼ 10^7 yr (e.g. ?). Furthermore, in this scenario, a spike in the accretion rate will occur during the inspiral phase as gas trapped between the two SMBHs is accreted (over a period of ∼ 10^5 yr). More detailed predictions of the accretion rate as a function of time during the binary phase were performed by ?. They argue that the accretion rate onto both SMBHs will vary on timescales corresponding to the binary period. For example, a ∼ 0.01 pc separation of two ∼ 3 × 10^6 M_☉ SMBHs leads to a variability period of ∼ 1 month, well suited for detection within the enormous sample of LSST AGN with high-quality photometric monitoring.

Another prominent observational signature of sub-pc binaries can come about from the interaction of one of the two black holes with the accretion disk surrounding the other. Such an interaction (and the resulting signal) is likely to be periodic, but with periods of order decades to centuries. Thus, we are likely to observe individual events and perceive them to be isolated flares. Some initial theoretical work attempting to predict the observational signature of such an interaction has been carried out by ?. Candidates for such systems have also been found. The best known example is OJ 287 where more than a dozen pairs of outbursts have been observed with a recurrence time between pairs of 10–12 years (e.g. ??, and references therein). Less persuasive claims for recurring outbursts have also been made for 3C 390.3 and PKS 0735+178 (??). The role of the LSST in identifying similar outbursts will be extremely important. After the initial identification, candidates can be studied further with continued long-term photometry and spectroscopy, in order to verify the nature of the system and derive its properties.
10.6.3 Mergers of Binary Supermassive Black Holes

LISA will have the capability to detect gravitational waves from SMBH mergers out to $z \sim 10$ or higher. In favorable cases, LISA will be able to localize a source to within a few arc-minutes to a few degrees on the sky. Furthermore, the gravitational-wave signal from binary SMBH coalescence serves as a “standard siren” that gives the luminosity distance to the event (limited by uncertainties in gravitational lensing along the line-of-sight), so LISA can provide a three-dimensional localization for a detected event. Identification of the electromagnetic counterparts to such events will be of great importance, both for studying the physics of accretion during SMBH mergers (e.g. ??) and for measurement of the redshift. The redshift can be combined with the luminosity distance measured by LISA to provide new constraints on cosmological parameters (e.g. ??).

The LSST data stream has the potential to be one of the most important resources for identifying the electromagnetic counterparts to SMBH mergers. During the final month before SMBH coalescence, there may be a periodic signature in the accretion luminosity due to the binary orbit, with a period of minutes to hours. The electromagnetic afterglow following the coalescence may be primarily luminous in X-rays (?), but reprocessing or ionization of emission-line gas could make the source detectable in the optical and near-infrared. And once the coalescence takes place, LSST will be able to localize the host object (?). Indeed, the LISA error volume may be small enough to include no luminous AGN other than the coalescing SMBH binary system itself; although the angular error region will be large, the three-dimensional nature of the error volume makes it a much more tractable problem to identify a unique optical counterpart to a merger event. The deep photometric redshift survey of galaxies and AGN provided by LSST over a large fraction of the sky should be invaluable for rapidly limiting the possible counterparts within the LISA angular-error region. In some cases, this three-dimensional location information from LSST may alone be sufficient to isolate one or a small number of counterparts that can then be investigated with narrower field telescopes.

10.7 Gravitationally Lensed AGNs

W. Niel Brandt, George Chartas

As discussed in the strong lens chapter (??), we estimate that in its single-visit images, LSST will discover $\approx 4000$ luminous AGN that are gravitationally lensed into multiple images (??). This more than ten-fold increase in the number of known gravitationally-lensed quasar systems, combined with the high cadence of observations of these systems will allow a variety of studies of these systems. We discuss the lensing-specific issues in ??, while here we focus on what we can learn about the AGN themselves.

10.7.1 Microlensing as a Probe of AGN Emission Regions

Resolving the emission regions of distant quasars is beyond the capabilities of present-day telescopes, and thus indirect methods have been applied to explore these regions. Such methods include reverberation mapping of the broad line region (e.g. ??), measurements of occultations...
of the central X-ray source by absorbing clouds (?), and microlensing of the continuum and emission-line regions (e.g. ?). GTR: WAY too many references here. Pick 3 or 4 that are representative.

Since LSST will be monitoring the fluxes of \( \approx 4000 \) gravitationally lensed AGN, it is ideally suited to tracking microlensing events in these systems. These events are produced by the lensing effect of a star or group of stars in the lensing galaxy. As the caustic network produced by the stars traverses the AGN accretion disk and other emission sources, regions near the caustics will be magnified. This causes uncorrelated variability in the brightnesses of the images of a lensed quasar, where the amplitude of the variability is determined by the ratio of the emission regions to the Einstein radius (e.g. ?). The largest components, such as the radio and optical emission-line regions, should show little or no microlensing variability. The thermal continuum emission from the disk should show greater variability at shorter wavelengths, corresponding to smaller disk radii and higher temperatures. GTR: Good place for a figure. Say overplotting a typical Einstein radius on a cartoon of the central engine. This wavelength dependent variability has been observed by ? and ?, and LSST should enable its study for large numbers of gravitationally lensed AGN.

### 10.7.2 LSST Microlensing Constraints on Accretion Disks

The first step in large-scale LSST microlensing studies will necessarily be the identification of the lensed AGN. Good candidates for lensed AGN will be identified using photometric redshift information for objects with small angular separations. These candidates may then be confirmed either via follow-up spectroscopic observations or via LSST studies of intrinsic variability. In the latter case, one will be searching for similar light curves from the putative lensed AGN images that are temporally shifted due to the different light-travel times associated with each image. The detection in deep LSST images of a foreground galaxy or cluster that could act as the lens will also aid the identification process and allow lenses to be distinguished from binary quasars.

Once the light-travel time delay is determined via a cross-correlation analysis from a given lens light curve, the data can be searched for evidence of microlensing. The LSST cadence will be sufficient for many microlensing analyses. However, to obtain even better temporal sampling (e.g., for rare, high-magnification events that have relatively short duration), it will make sense to target identified microlensing events with additional telescopes. Ultraviolet and X-ray observations using facilities with sufficient angular resolution, such as Chandra in the X-ray band, will also be pursued as appropriate.

The large number of lensed quasars from \( z \approx 1–6 \) will allow a search for evolution of AGN structure across this redshift range and a large range of luminosity and Eddington ratio. For example, a change in the mode of accretion from the standard thin accretion-disk solution may be revealed by changes in the scalings between wavelength, emission radius, and SMBH mass. Recent studies of AGN luminosity functions in the X-ray and optical bands indicate an anti-hierarchical evolution of AGN, such that lower luminosity AGN peak in comoving number density later in cosmic time (e.g. ??). Microlensing analyses will help to determine whether this “downsizing” behavior in luminosity (??) is accompanied by downsizing in accretion-disk size and SMBH mass.