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MULTIEPOCH SKY SURVEYS AND THE LIFETIME OF QUASARS

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ABSTRACT

We present a new method to measure the episodic lifetime of quasars with current and future large-scale sky surveys. Future photometric observations of large samples of confirmed quasars can provide a direct measurement (or interesting lower limit) to the lifetime of an individual episode of quasar activity (t_Q) and potentially enable the study of post-quasar host galaxies. Photometric observations of the quasars found by the Sloan Digital Sky Survey (SDSS) and 2dF Survey could, with a time baseline of ten years, determine t_Q to within a factor of two if $t_Q < 10^5$ years, or set a lower limit to the quasar lifetime. Multiple-epoch, precise photometry with the proposed *Large Synoptic Survey Telescope* could test more complex models for quasar variability and mean quasar luminosity evolution. These observations could also constrain the rate that tidal disruptions of single stars produce quasar luminosities.

It is possible to reverse the order of this investigation; previous-epoch plate material, such as the Digitized Sky Survey, can be used to determine if any of the SDSS quasars had not yet turned on at the time of these prior observations. Measurements of the entire SDSS quasar sample over the ~ 50 year baseline provided by these plates can potentially be used to estimate t_Q to within a factor of two if $t_Q < 10^{5.5}$ years, provided quasar variability can be accurately characterized and the detection efficiency and photometric calibration of the plate material can be well determined. These measurements of t_Q will have comparable quality to existing, more indirect estimates of the quasar lifetime. Analysis of the 3814 quasars in the SDSS Early Data Release finds that t_Q must be larger than approximately 20,000 years.

Subject headings: surveys – galaxies: active – quasars: general

1. INTRODUCTION

The quasar lifetime (t_Q) is an important timescale for supermassive black hole growth and determination of the mechanism(s) that fuel Active Galactic Nuclei (AGN). The net time that black holes are radiating at quasar luminosities, and therefore accreting at approximately the Eddington rate, sets the importance of luminous accretion for the production of the present-day space density of dormant, supermassive black holes. If this lifetime is longer than $t_Q > 10^7$ years, then a quasar phase would have led to the accretion of much of the mass in the largest present-day supermassive black holes. However, the low space density of quasars, even at high-redshift, then implies that a quasar phase was relatively rare and not all supermassive black holes were quasar hosts. In contrast, shorter quasar lifetimes require more of the present-day supermassive black hole population to have been quasars, but then to have accreted a smaller fraction of their total black hole mass as quasars.

Most estimates of the net quasar lifetime produce values in the range $t_Q = 10^6 - 10^8$ years, or lower limits that are consistent with these values (for a recent review see Martini 2003). These estimates are generally based on either integral or demographic arguments, which combine data on the present-day population of supermassive black holes and the accretion by the high-redshift quasar population (e.g. Sołtan 1982; Haehnelt et al. 1998; Yu & Tremaine 2002), or incorporate quasars directly into models for galaxy evolution (Kauffmann & Haehnelt 2000). However, most demographic models only constrain the net time that a supermassive black hole is radiating above the luminosity threshold for quasars and do not address the possibility that a supermassive black hole goes through multiple, episodic quasar phases that sum to produce the net lifetime. The episodic lifetime is an important parameter for the accretion physics, as it is the timescale that an accretion disk can maintain accretion at approximately the Eddington rate. Existing constraints on the episodic lifetime suggest $t_Q > 10^4 - 10^5$ and are primarily based on the radiative properties of quasars. These lower limits are due to the minimum lifetime required to explain the proximity effect in the Lyman–α forest (Bajtlik et al. 1988; Scott et al. 2000) and the sizes of ionization-bounded narrow-line regions (Bennert et al. 2002). A recent observation of the transverse proximity effect in He II does imply a longer lifetime of $t_Q \sim 10^7$ years (Jakobsen et al. 2003); however there is currently only one such observation.

Measurement of both the episodic and net lifetimes of quasars are important to determine the methods that trigger quasar activity, as well as the physics of the accretion process. If net and episodic lifetimes are similar, and by implication long, quasars could be produced by the relatively rare merger of approximately equal-mass, gas-rich galaxies. This is currently the most favored mechanism invoked to explain the mass accretion rates necessary to fuel quasars, as well as their rapid decrease in space density at low redshifts (Carlberg 1990; Barnes & Hernquist 1992). In contrast, if the episodic lifetime of quasars is significantly less than the net lifetime, then quasar activity must be triggered by a phe-

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nomenon that is more frequent than large galaxy mergers. Some fraction of quasars could also be powered by the tidal disruption of individual stars as they pass near peribarathron (Hills 1975; Young, Sheilds, & Wheeler 1977), which could produce quasar luminosities for on order one year (Ulmer 1999). The current estimates and limits on both the net and episodic lifetimes are still uncertain by several orders of magnitude due to the quality with which the current data are fit by models, and the assumptions of the models themselves. In the present work we describe a method that could improve the limit on the episodic lifetime by approximately two orders of magnitude and determine if the episodic and net lifetimes are comparable.

The most direct method to determine t_Q is to actually measure a quasar turn on and off. This is impractical for any given quasar, given the long lifetime implied by the methods described above, but is possible for observations of an ensemble of quasars, such as are now being produced by the 2dF (Croom et al. 2002) and SDSS (York et al. 2000) surveys. The 2dF survey has produced a final catalog of 23,424 quasars, while the SDSS survey plans to complete a catalog of 100,000 quasars over the next several years. In the next section we provide a detailed calculation of how well t_Q can be computed from these spectroscopically-identified quasar samples when compared with photometry from at least one additional epoch. We also describe how the SDSS quasar catalog could be compared to the existing *Palomar Observatory Sky Survey* (POSS), particularly in light of the lower-quality and comparable sensitivity of these plates. This method is illustrated through application to the SDSS Early Data Release (EDR) quasar catalog. We conclude with a discussion of the implications of these measurements or upper limits on t_Q in the final section.

2. METHOD

We shall first examine the problem of quasar lifetimes with a simple model for the quasar luminosity: the quasar is either "on" or "off" with a characteristic on lifetime t_Q. In this scenario, the probability that any quasar will turn off over a time baseline Δt is $P_{off} = \Delta t(z)/t_Q$, where $\Delta t(z) = \Delta t/(1+z)$ is the time baseline in the quasar frame from the spectroscopic identification to the second, photometric epoch. For a sample of N quasars where only N_{on} are observed to be on at the second epoch, the lifetime can then be directly calculated as

$$t_Q = \frac{\Sigma \Delta t(z_i)}{\Sigma i - N_{\rm on}} \quad (1)$$

where this assumes that a quasar will definitely be detected if it is on at the second epoch. Here we adopt the same definition of a quasar as the SDSS EDR quasar catalog: an AGN brighter than $M_{i^*} = -23$ mag (Schneider et al. 2002). For a spectroscopically-identified quasar with one additional, photometric epoch we consider a quasar as on if it is above this luminosity threshold, and off if it is fainter than this limit. The limitations of this assumption are discussed in §3.

One survey that could provide the second epoch photometric observation for the SDSS and 2dF quasar samples is the proposed *Large Synoptic Survey Telescope* (*LSST*; Tyson et al. 2002). The *LSST* is intended to regularly survey the entire visible sky to a depth many magnitudes fainter than the limit of the SDSS and 2dF quasar samples. This telescope will therefore easily obtain high-quality photometry of all of the quasars in the final 2dF and SDSS catalogs provided they are still on at the time of the *LSST* observations. We have modeled the quality with which the SDSS and 2dF samples could be used to measure the quasar lifetime by generating mock catalogs with a range of lifetimes and the same magnitude and redshift distributions as the SDSS EDR. Figure 1 shows the quasar lifetimes and uncertainty in t_Q attainable with this second epoch *LSST* observation. If the *LSST* obtains a second baseline measurement of these 120,000 quasars ten years after their initial spectroscopic identification, then this will measure t_Q to within a factor of two if $t_Q < 10^5$ years, or otherwise set a lower limit to the quasar lifetime if no quasars have been observed to turn off. The upper and lower limits to the quasar lifetime are set by the length of the time baseline and the probability that no quasars will actually be observed to turn off over this baseline, respectively. For long values of the lifetime only a small number of quasars will be observed to have turned off; we have calculated the one-sided, $1-\sigma$ confidence limits on the number of quasars that are off using Poisson statistics as described in Gehrels (1986).

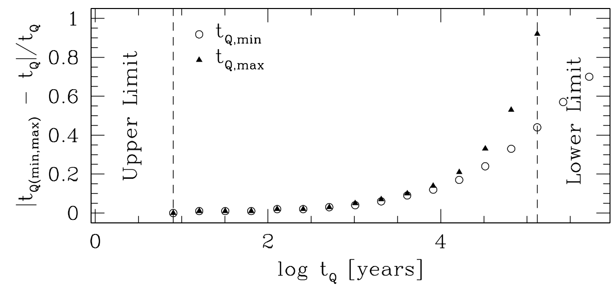

FIG. 1.— Quality of the potential measurement of the quasar lifetime by the *LSST* as a function of quasar lifetime. The constraint or measurement of t_Q is based on reobservations of 120,000 quasars ten years after their epoch of spectroscopic identification, which provides a net time baseline of approximately 500,000 years for the redshift distribution of the SDSS EDR. The magnitude of the lower (*open circles*) and upper (*filled triangles*) bounds on t_Q have been computed with Poisson statistics.

For second-epoch survey material that does not extend many magnitudes below the limits of the spectroscopic sample, the sensitivity limit, quasar variability, and the quality of the photometric calibration could all produce a false signal of off quasars. These additional effects can be accounted for by assigning a weight w_i to each quasar that quantifies the probability that it could be detected at the second epoch, given an assumed magnitude distribution based on the spectroscopic epoch, a parameterization of quasar variability, and the sensitivity of the second epoch photometric survey:

$$w_i = \int dm_{ij}\, P_m(m_{ij}|\mu_i)\, P_d(m_{ij}) \quad (2)$$

The expected magnitude distribution for the quasar $P_m(m_{ij}|\mu_i)$ can be calculated from a Gaussian distribution centered on its assumed mean magnitude μ_i at the time of identification, as well as the photometric uncertainty and quasar variability. Due to a variant of the Eddington bias, this mean magnitude will on average be fainter than the magnitude m_i at the time of spectroscopic selection because of quasar variability σ_V, the photometric uncertainty σ_P, and the slope of the quasar number-magnitude relation. The variability of quasars is commonly parametrized with a structure function (Simonetti et al. 1985; Hughes et al. 1992) and long term monitoring of quasars shows that the amplitude of the variability increases with time (Hawkins 2002). The width of the distribution of likely quasar magnitudes at the second epoch is thus the quadrature sum of the photometric uncertainty and the time-dependent variability: $\sigma(\Delta t) = \sqrt{\sigma_P^2 + \sigma_V^2(\Delta t)}$. This magnitude distribution is then convolved with the detection probability $P_d(m_{ij})$ for a quasar with magnitude m_{ij} at epoch j. With this weighting function the total number of expected quasars in the second epoch becomes the sum of these weights Σw_i and the total time baseline available becomes $\Sigma w_i \Delta t(z_i)$. The equation for the lifetime is rewritten:

$$t_Q = \frac{\Sigma w_i \Delta t(z_i)}{\Sigma w_i - N_{\rm on}}. \quad (3)$$

A particularly useful set of archival observations are the POSS-I plates obtained in the 1950s. All of these observations have been digitized, are publicly available on CDROM, and provide the longest time baseline for the SDSS quasar catalog. As above for the *LSST* calculation, we have used the redshift and magnitude distribution of the SDSS EDR quasars to model the sensitivity of the SDSS + POSS-I to the quasar lifetime. For regions which were not covered by the POSS-I survey, we have used the more recent POSS-II data from the 1980s. While the 23,000 2dF quasars will also be valuable when combined with future *LSST* observations, they are not suitable for comparison with the archival plate material as the spectroscopic quasar candidates were identified from these plates.

The first step in this analysis was the photometric calibration of the POSS plates, which was carried out with USNO stars selected from the same plates as the EDR quasars, to have similar colors (Richards et al. 2002), and small proper motions. This produced a catalog of ~ 9800 stars that were used to calibrate the POSS plates directly onto the SDSS magnitude system. The rms uncertainty in the photometric calibration is ~ 0.4 mag. These same stars were then used to determine the detection efficiency as a function of magnitude by measuring the number of stars identified with SExtractor (Bertin & Arnouts 1996) in 0.5 mag bins. The USNO catalog is complete to $V = 21$, which is fainter than the POSS-I limit and the magnitude for SDSS quasar selection. The EDR quasars were detected using the same SExtractor parameters and requiring that the source on the POSS-I plate be within $4''$ of the SDSS coordinates. Finally, quasar variability was parameterized with the structure function calculated by Hawkins (2002). This structure function, which is similar to that recently derived from the SDSS EDR quasars by de Vries, Becker, & White (2003), was used to set the width of the expected quasar variability distribution as a function of time baseline in the quasar frame. Figure 2 shows the quasar lifetimes and uncertainty in t_Q attainable with a combination of the 100,000 SDSS quasars and the POSS epoch. These data will thus in principle be able to measure the quasar lifetime if $t_Q < 10^{5.5}$, although in practice the sensitivity will be somewhat less due to uncertainties in quasar variability and the photometric calibration of the plates. Application of this method to the SDSS EDR sample sets a lower limit of $t_Q > 20,000$ years on the episodic quasar lifetime.

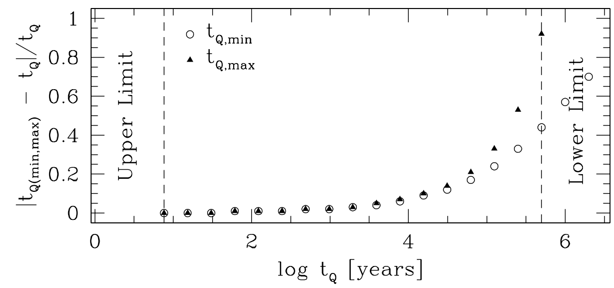

FIG. 2.— Same as Figure 1 for a comparison of the 100,000 quasars expected in the SDSS sample with the POSS observations. The time baseline in this case is approximate two million years. In practice, the constraint on t_Q from the POSS comparison will be limited by uncertainties in quasar variability and the POSS photometric calibration.

3. DISCUSSION

The present lower limit of $t_Q > 20,000$ years from the SDSS EDR quasar sample is in agreement with the lower limits to t_Q from the radiative arguments outlined in the Introduction. This limit can be improved by approximately the factor of 30 increase in sample size expected from the final SDSS quasar sample. The potential measurement or limit of $t_Q > 10^{5.5}$ years from the full sample will either measure t_Q or produce an improved lower limit to the episodic lifetime of quasars. Future observations of the full quasar sample with the LSST and a ten-year baseline could push the lower limit to $t_Q \sim 10^6$ years through use of the combined baseline provided by POSS and *LSST* data. These observations will also be able to set interesting limits on the rate at which tidal disruptions of stars produce quasar luminosities.

The measurement of t_Q via *LSST* observations of the complete SDSS and 2dF quasar samples will provide a comparable constraint on t_Q to many of the existing, indirect estimates from demographic arguments, which typically find values of $t_Q \sim 10^7$ years (Haehnelt et al. 1998; Kauffmann & Haehnelt 2000; Yu & Tremaine 2002). If the sky-survey measurement or lower limit and these other estimates of t_Q remain comparable in the face of improved data, this will be a strong validation of the assumptions of radiative efficiency, black hole mass function, and Eddington fraction that are key components of the demographic models.

Observations with the *LSST* will also provide superb measurements of quasar variability, which motivates a more careful consideration of our definition of the episodic quasar lifetime. A particularly important question is what is meant by a quasar that is off, relative to a quasar that is instead experiencing extreme variability. Here we have defined a quasar as off if it becomes fainter than the absolute magnitude $M = -23$ used to define the quasar sample. This definition is motivated by the small number of available epochs for the quasars in the POSS data and the poor photometric precision of the plates, which make it difficult to characterize the variability of individual quasars. Our definition, however, allows for the spurious identification of off quasars due to misclassified, extremely variable objects, or simply variable quasars near the luminosity limit that defines the quasar class. In principle, a quasar should not be classified as off if it has temporarily faded to become a lower-luminosity AGN and then subsequently increases in brightness to become a quasar again. For quasars with only a small number of epochs, particularly of poor photometric precision, this point will be hard to circumvent.

The multiple-epoch and greater precision observations with the *LSST*, however will allow this point to be addressed in two ways. First, extremely variable quasars can be identified and not included in the sample through a variability cut for the lifetime estimate. A second approach is to include even these extremely variable quasars, yet require that they fade several magnitudes below the defining luminosity of a quasar for some number of years before they are formally classified as off. This later approach is more appealing as eliminating the most variable segment of the quasar population may eliminate quasars that are near the end of their lives. If the quasar has turned off, whether completely or is simply temporarily quiescent, then this will offer an unprecedented opportunity to study the quasar host galaxy.

The luminosity and variability evolution of quasars can be considered in greater detail with the multiple-epoch *LSST* observations. We have adopted the simple assumption that quasars undergo no luminosity evolution while they are on, other than their known variability about some constant mean. Many models for quasars, however, adopt an exponentially decaying luminosity (e.g. Haehnelt et al. 1998). If the mean luminosity of a quasar decays exponentially over an *e*–folding timescale $t_Q{}'$, rather than experiencing a simple shut off after t_Q, then the SDSS and *LSST* photometry could be used to search for a mean decrease in the luminosity of the quasar population, provided it is relatively short. For an assumed photometric uncertainty of 0.02 mag and a baseline of ten years, a dataset of 100,000 quasars could in principle measure a change in mean luminosity for a characteristic decay time of close to $t_Q{}' \sim 10^5$ years, although in practice quasar variability will limit the sensitivity of such a measurement to much shorter characteristic decay timescales.

Longer lifetimes, whether in the simple on–off model or with more complex luminosity evolution, could naturally be even better investigated with yet larger samples. While a significantly larger spectroscopically-identified sample is unlikely in the near future, a larger color-selected sample is possible. Based on studies with the color-selection algorithms used for the SDSS quasar sample, there are regions of color space that are almost exclusively occupied by quasars (Richards et al. 2002). Thus large numbers of quasars could be identified through color-selection alone, either in the SDSS or with *LSST*, and then monitored over a number of years. While the remaining contaminating population must be considered, these are almost exclusively non-variable objects such as white dwarfs, and many of these contaminants could be identified via their proper motions.

Completion of the SDSS should also produce improved estimates of the net lifetime of quasars from other techniques such as quasar clustering (Martini & Weinberg 2001; Haiman & Hui 2001). A preliminary comparison of the 2dF clustering measurements to the models in Martini & Weinberg (2001) suggest the quasar lifetime may be as short as $t_Q \sim 10^6$ years. If refined estimates based on SDSS measurements continue to point toward a shorter lifetime, then the net lifetimes determined from clustering will be comparable to the range of lifetimes probed by the method outlined here and these two methods could determine if the net and episodic lifetimes are comparable. If they are, then supermassive black holes only experience one quasar phase and the mechanism that ignites and fuels quasar activity is a relatively rare event. In contrast, if the episodic lifetime is much shorter than the net lifetime, then quasar activity must be triggered by additional mechanisms than just the relatively rare mergers of gas-rich galaxies.

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