Letter of Intent for After SDSS-IV: All-Quasar Multi-Epoch Spectroscopy

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MOTIVATION: Quasars, the most luminous accreting compact objects in the Universe, trace the co-evolution of galaxies and black holes across $> 90\%$ of cosmic time. Spectroscopic variability in quasars uniquely probes supermassive black hole (SMBH) masses, accretion disk properties, accretion rate changes, dynamical changes in the broad emission line region, outflows and beyond. We intend to propose the first wide-area multi-epoch spectroscopy program, focused on long-term quasar variability. Spectra sampling timescales of several months to more than a decade, and spanning a wide redshift and luminosity range provide information that is completely unavailable to the many current and upcoming photometric time domain imaging surveys, yet provides powerful synergies for understanding their content. Supplementing and contrasting legacy SDSS spectra with > 2 new epochs allows both confirmation of variability and a taste of evolution e.g., constraining structural changes in the broad emission line region, testing binary SMBH models, detecting evidence for outflow acceleration, and many other possibilities.

Continuum variability: Within a large sample, variations can be extreme, as in the recently-discovered "changing-look" quasars (CLQs), where both UV/blue continuum and broad emission lines effectively disappear. This remarkable phenomenon may be caused by intermittent fueling or strong episodic obscuration of the central engine. As such, CLQs directly constrain quasar duty cycles and their effects on the circumnuclear medium, challenging the standard AGN unification picture, and unveiling host galaxy stellar populations with the quasar 'off'. Large sample continuum variability studies of normal quasars are also key to distinguish the role of overall accretion rate changes vs. e.g., localized temperature fluctuations on a variety of timescales.

Broad Emission Line Variability: Our AS4 All-Quasar Multi-Epoch Spectroscopy (AQMES) program would broadly sample a host of SMBH accretion phenomena, by ensuring that several (typically 3-5) spectroscopic epochs exist for $\sim 10^5$ quasars within the SDSS imaging footprint. AQMES is strongly complemented by the AS4 Reverberation Mapping (RM) program (Shen, PI), which intensively samples shorter (day to month) timescales for a $\sim 60\times$ smaller sample. While broad emission line (BEL) strengths vary on day/week (light travel) timescales in response to variations in the ionizing continuum (allowing the RM studies), *major* variations of the BEL profiles that reveal dynamical and structural changes in the BEL region take years. The large AQMES sample also allows us to probe processes across a much wider variety of quasar types than is accessible to RM. However, the two approaches complement and reinforce each other. For instance, the RM sample provides the best possible SMBH mass estimates, with calibrations applicable across AQMES (e.g., distinct radius-luminosity relationships relevant to different emission lines and redshift regimes).

Absorption Line Variability: Absorption line variabilities provide valuable constraints on the structure, location, dynamics and evolution of quasar outflows that is not available by other means. This information is critical to our understanding of the outflow acceleration physics, the coupling of outflows to black hole growth and accretion processes, and the kinetic energy yields available for feedback to galaxy evolution. Some $\sim 15\%$ of quasars have broad absorption lines (BALs), while $\sim 50\%$ have narrow line (NAL) outflows. At a resolving power of ~ 2000, intrinsic NALs may only be reliably distinguished from gas in intervening structures by their variability.

To understand the dynamics of gas near the quasar central engine, we must study all these phenomena. Robust, predictive models are sorely needed, but require better observational constraints from large samples. In just a few years of repeat observations for $\sim 10^5$ quasars, AQMES expects to observe statistical samples of rare phenomena that may typically occur only after many millennia in a given object, including e.g., tidal disruption events and microlensing. This is one of the primary aims of our proposal – to explore the breadth of quasar spectroscopic variability and uncover new phenomena to advance our understanding of quasar central engines. A large sample further allows disentangling correlated dependences of such phenomena on e.g., luminosity, SMBH mass, and accretion rate.

PROJECT SCALE: We will propose 2 to 3 *new* spectroscopic epochs for up to 100 ($r < 22$) quasars deg^{-2} over $\sim$2500 deg^2, totalling nearly 3/4 million quasar spectra. eBOSS-like tiling (5 deg^2 per plate) still leaves more than 100 fibers/deg^2 for other compatible spectroscopy projects, such as repeat spectroscopy of selected close stellar binary candidates identified in SDSS or TDSS, or *first* epoch spectroscopy for identification and characterization. Such new targets could include eROSITA X-ray sources (Merloni), local (morphologically extended) obscured or variable AGN, or newly-discovered variables from a complementary time-domain perspective outlined in the Appendix.

Since S/N is key for spectroscopic variability studies, we propose exposures of up to 2 hours using the BOSS spectrographs on the Sloan 2.5m. At 5 deg^2 per plate our survey would require $\sim$1500 pointings (at least 500 plates) and $\sim$3000 hours of dark time observing. At about 4.5 plates per night, assuming 50% clear nights and 10% for additional losses, we would require 730 dark nights in total, or $\sim$4 years. These figures are reasonable guidelines, but scheduling and sky coverage of our program are highly flexible and the optimal strategy will likely depend on time-sharing with other dark time programs. We note that, within the ELG regions of SDSS-IV/eBOSS, TDSS plans a pilot of AQMES, re-targeting known quasars within TDSS $\sim$10 deg^{-2} allotment.

The purpose of this bold new AQMES sample is threefold. First, measuring all possible shifts in the spectral states of quasars over a 5–20 year baseline would necessarily capture all of the most interesting, rare phenomena (such as the CLQs). Second, by including *all* quasars, such a sample would provide the first accurate population statistics of the dynamics of the emitting and absorbing gas. Third, co-addition of multiple epochs of spectroscopy for fainter SDSS quasars would invigorate the plethora of quasar studies requiring higher S/N ($\sim$2.5$\times$ better for 4 total epochs). For example, improved statistics on intervening (Lyα forest and metal-line) absorbers would dramatically enhance our understanding of their temperature-density relation, the thermal history of the IGM and the cosmic evolution of IGM/CGM enrichment. While our boldest sample would require $\sim$100 fibers deg^{-2} (e.g., Table 4 of Myers et al., 2015, *ApJS*, 221, 27) high priority sub-samples could be chosen to fill fibers at sparser levels, for instance: ▶ Bright (mag$<$ 20) SDSS QSOs for high S/N ($\sim$10 deg^{-2}) ▶ Brighter (mag$<$ 19) strongly variable QSOs with rich single-band lightcurves from e.g., Catalina, PTF (iPTF, ZTF), etc. ($\sim$5 deg^{-2}) ▶ SDSS, Stripe 82, or TDSS QSOs with known spectroscopic variability ($\sim$2 deg^{-2}) ▶ BAL and NAL QSOs for absorber and outflow studies ($\sim$4.5 deg^{-2}) ▶ AGN with double-peaked or asymmetric BELs; either amenable to detailed disk fitting or indicative of potential binary SMBH ($\sim$0.1 deg^{-2}) ▶ Changing Look AGN candidates ($\sim$0.5 deg^{-2}) ▶ Blazars (BL Lacs and flat-spectrum radio quasars; $\sim$0.5 deg^{-2})

AS4-AQMES has flexibility for total sky area, particular sky regions, start date, and number of epochs, providing adaptability to mesh with other programs.

OPERATIONS SKETCH: We require standard eBOSS/TDSS-like dark-time operations with no new instrumentation, resources, capabilities, infrastructure, or major software development. We estimate that our base program would run for 4 years with a great deal of flexibility. We anticipate that data distribution could mimic eBOSS/TDSS closely. Given the low risk of our program, our cost estimate would be similar to SDSS-IV operations, and would thus amount to a pro-rated share (i.e. 50% for dark time, fiber fraction etc.) of the $\sim$\$2.4M per year current costs.

EDUCATION/PUBLIC OUTREACH: As just one specific example, we will modify the open-source xSonify code with its author Dr. Wanda Diaz-Merced, to convert spectra to sound. Web-based labs will allow students (not only the blind and visually-impaired) to *hear* differences between quasars and stars, and to viscerally understand redshift and spectroscopic variability.

STRENGTHS: Large quasar samples with multiple spectroscopic epochs, available only with a new SDSS survey, are critical for all our science goals. By opening multiple new scientific avenues, AQMES ensures AS4 relevance in the era of LSST and DESI (which will not accommodate programs that might degrade cosmological studies). AQMES is flexible, inexpensive and low-risk. The power of time-domain science increases as time series are extended, so AQMES offers a lasting legacy, building on the heritage of superb Sloan spectroscopy since SDSS-I.

COLLABORATORS

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APPENDIX
Some Additional Synergies

We propose high-impact returns from repeat, large-scale 2.5m spectroscopy within AS4, and above we specifically call attention to quasar science synergies with some other relevant AS4 white paper programs of which we are aware (e.g., RM and eROSITA). Here, we also add a complementary note that many of the science cases considered under the original AS3/TDSS proposal related to first epoch spectroscopic classification of variables may have renewed relevance in the AS4 time-frame, at the level of hundreds of potential targets per square degree to modest magnitudes of $m < 21$. For example, ZTF (whose photometry is also well matched in depth to corresponding Sloan optical spectra in modest exposures, and includes Milky Way coverage), Gaia, PanSTARRS-2, ATLAS, etc. should also have completed extensive catalogs by the AS4 timeframe – catalogs by then public, studied, and well-understood – to add to those of PanSTARRS-1, Stripe 82, Catalina, PTF, iPTF, etc. Combined, these will provide millions of high-confidence photometric variables and their lightcurves, e.g., permitting selection and spectroscopic targeting of subclasses with special-interest lightcurve-character. At the brighter end of LSST, which will also start in the AS4 time-frame, rich light curves will provide a slew of further variables. Several thousands of square degrees of LSST will be accessible from the North and far more in the South. Indeed, with other compelling interest in AS4 telescope options there, extension to the South (e.g., using the LCO 2.5m) is feasible, and would enhance access for characterization of LSST-selected variables or transients, for which the white papers of Dai et al. on ToOs and Huehnerhoff et al. on robotic fiber positioners may become relevant. AQMES in darker-time also would mesh well operationally with APOGEE time-domain related programs in brighter-time, providing an alternate unifying time-domain theme that exploits complementary extant instrumentation, with science spanning from stars nearby in the Milky Way, to quasi-stellar objects and their supermassive black holes in the distant Universe.