Report of the Time Domain Astronomy (TDA) Subcommittee of the AS4 Futures Committee
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Time-domain astronomy was a common theme in many of the AS4 white papers received in fall 2015, with ideas ranging from spectroscopic follow-up of objects selected from independent time domain surveys (transiting exoplanet hosts, transients, etc.) to objects exhibiting intrinsic time variable spectra (AGN, variable stars, binaries, etc.). Ideas emerging from the white paper process and committee discussion include several compelling uses of the APOGEE and BOSS spectrographs in the realm of time-domain astronomy. These ideas include the following: (1) to enable “precovery” science leveraging upcoming exoplanet space missions that will produce large numbers of ultra-precise stellar light curves, (2) to conduct multi-epoch spectroscopy on a wide range of variable sources, (3) to advance machine-learning capabilities leveraging the upcoming LSST and other photometric time domain surveys, and (4) to support rapid and long term follow-up of transients. We briefly describe each of these:

1. Spectroscopic observations of stars with ultra-precise light curve observations : All-sky spectroscopic characterization of exoplanet host stars and other targets of interest from Kepler, K2, TESS and PLATO.

> The NASA Kepler mission has revolutionized exoplanet science through the discovery of thousands of transiting planets around distant stars. Crucially, the determination of the physical properties of the exoplanets depends directly on the properties of the host stars — namely the stellar effective temperature, surface gravity, and metallicity. However, because there did not exist a comprehensive, accurate catalog of stellar properties for the Kepler stars in advance of the mission, the community remains in a backlogged state of “catch up” as we scramble to recover the stellar properties through follow-up observations only *after* the planets have been discovered. TESS and PLATO[1] are the successor missions to Kepler, scheduled for launch in late 2017 and 2024, respectively. Each will perform nearly-all-sky observations of ~$2x10^5$ very bright stars (4-12 mag), in the hopes of discovering terrestrial planets that are most amenable to atmospheric characterization studies with JWST. The expected delivery of Gaia parallaxes, 3-space motion, and spectra for virtually all of these stars allows excellent temperature and gravity determinations in advance of the exoplanet discoveries. However, a crucial gap will remain in the determination of metallicities, and especially detailed chemical abundances.

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[1] PLATO mission nominal parameters: Launch in 2024; FOV = 2250 deg^2 (that is 22.5x Kepler FOV); Observing = Two FOVs observed for 2.5 yrs each, so in total this is 50x Kepler FOV but with TESS mag range, and there will also be a number of TESS-like short-duration stare-and-step fields; FOV locations = -60 dec and +45 dec, near the Galactic plane (i.e., mostly near the Galactic plane which TESS avoids).
TESS mission nominal parameters: Launch in 2017; FOV = 1/26 of 4pi ster; Observing = Each FOVs observed for ~30 days each, tiling full sky over 2 years; FOV locations = Full sky is tiled, however ecliptic poles are viewed continuously for 1 year each (i.e., the same as the JWST continuous viewing zone), and the Galactic plane (roughly +/- 10 deg) is avoided.

A highly multiplexed, dual hemisphere, high-resolution spectroscopic survey starting as soon as 2018 or 2019, with a pipeline for delivering a full suite of stellar properties would provide “precovery” of these stellar properties in advance of PLATO launch (and during the TESS analysis phase), thus enabling rapid science as soon as the planet discoveries are made. The ASPCAP pipeline has already been developed and vetted to extract fundamental stellar parameters for AFGK-type stars (Perez et al 2016); extension of the pipeline to hotter (B-type) and cooler (M-type, down to M5 for TESS) stars could enhance the impact of a TESS precovery survey. Note that other planned spectroscopic surveys such as LAMOST will have much more limited capabilities, especially with regard to precision radial velocities and full-suite elemental abundances. Moreover, including a contamination check on the APOGEE spectra could enable the precovery data to be used as a first-order check on contamination of TESS/PLATO stars by nearby/background stars. Finally, if radial velocity precisions on the order of 100 m/s are possible, then even just two epochs per star would enable rapid vetting and elimination of most types of exoplanet false positives. The ATLaS white paper described the case for a search for stellar and sub-stellar companions with the APOGEE spectrographs. Improvements in spectrograph stability and fiber positioners would provide enhancements to this capability. This program could dovetail with a precovery mission.

More generally, the experience of Kepler is that there is a broad community interested in detailed study of objects that have ultra-precise light curve observations of the sorts produced by Kepler, K2, TESS, and PLATO. Thus one can envision a large-scale scientific program to deliver a (possibly multi-epoch) spectroscopic survey of a very large sample of stars observed or to be observed by those missions, yielding an unprecedented catalog that marries detailed sub-mmag precision time-domain photometry with high-quality spectra and the full suite of stellar parameters that can be derived from those spectra. Finally, one might envision such a program being carried out in concert with a rapid time-domain follow-up program (see below), in which the target lists for spectroscopic observations are drawn from a large all-sky list of potential targets (e.g., from Kepler, K2, TESS, PLATO) but determined on the fly, slaved to the specific pointing needs of the rapid follow-up targets.

2. Classification and Multi-epoch spectroscopy of variable sources

While the era of time domain astrophysics has been ushered in largely to explore explosive transient phenomena, there exist exciting opportunities to understand the detailed astrophysics associated with recurring and ongoing phenomena (such as RR Lyrae, Cepheid, W UMa star atmospheres and novae) and the multi-year evolution of fast processes (such as stellar winds, mass loss, falling evaporating bodies), and to relate them to explosive transients and the ultimate fate of stars. ZTF, Gaia, TESS, PLATO, etc. will identify a very large number of photometrically variable sources. These identifications can seed large-scale spectroscopic studies for classification, radial velocities, and population and structure studies of binaries and variables. SDSS-type facilities can provide the required intensive spectroscopic follow-up routinely for large numbers of similar sources. This is currently not being explored by any existing facility on large scales and therefore represents a unique opportunity for ARC. The niches of higher cadence spectroscopic follow-up of variable sources and/or spectroscopic follow-up of the brighter population of variable sources (e.g. those detected and characterized by Evryscope; that provides mmag minute-cadence photometry for stars brighter than V=12 covering >8000 square degrees continuously) could be filled by AS4. Potential synergies with simultaneous Evryscope+AS4-South observations of a subset of variable sources, or with the deployment of a low cost Northern-hemisphere Evryscope analog at APO could yield unique TDA of variable stars in a cost effective manner.

As a concrete illustration, by 2020 the ZTF survey will have publicly released an average of 750 observations of each field in the Northern sky. With a median limiting magnitude of ~20.4, the variable objects ZTF identifies will be very well-suited to BOSS classification. Similarly, *Gaia* photometry will be available for a similar set of objects with higher photometric precision but more irregular cadence, in addition to detailed astrometric information. Cross-correlation with the public PanSTARRS-1 catalog will enable combined color and variability selection in the manner of SDSS Stripe 82, but over nearly 3 pi steradians. In particular, ZTF's survey will provide unprecedented variability coverage of the Northern Galactic Plane, a rich area as yet poorly explored in the optical time domain. (*Gaia* will only obtain radial velocities for sources brighter than ~16th mag, about 10% of its catalog.)

During SDSS-IV, the Time Domain Spectroscopic Survey (TDSS) is using the BOSS spectrographs to accomplish some of this science with few epoch visits, particularly for quasar variability, and another program is using the BOSS spectrographs for reverberation mapping of AGN. The 3.5-m has also excelled at following up objects discovered in SDSS throughout the first four surveys and in particular during SDSS-II when follow-up spectroscopy of supernovae was a scheduled program every other night during the SDSS-II supernova survey.

Continuation of a TDSS type project was described in one of the white papers that was received (Green et al.), and continuation of reverberation mapping was described in another white paper (Shen et al.). In particular, increasing the sample size of newly discovered "changing-look" quasars (Ruan et al 2016) via few epoch visits could help elucidate their origin and help probe the m-sigma relationship as a function of cosmological distance. A third time-domain white paper by Troup et al. described a survey called ATLaS, which would be a stellar and sub-stellar companion search using APOGEE radial velocity monitoring. A potentially exciting new area for AS4 to explore was described in a white paper by Brogi et al, which discusses exoplanet transmission spectroscopy of bright targets (e.g. from TESS) using APOGEE. These opportunities could potentially be combined and expanded into a larger time-domain spectroscopic monitoring program, perhaps also involving the 3.5-m.

3. Advancing machine-learning capabilities in the LSST era: All-sky spectroscopic characterization of stars to establish methods for stellar characterization via time-domain photometry.

The Large Synoptic Survey Telescope (LSST) is planned to begin observations in about 2020, at which time it will begin to produce multi-band photometric light curves for ~10^9 stars in the Milky Way and Magellanic Clouds, including many types of variable stars, as well as novae, supernovae, and other very distant objects that become temporarily and/or suddenly bright. A major unresolved problem is how best to determine the nature of each LSST object, especially in the context of near-real-time characterization of "transients". Because of the magnitude depth of LSST, all but the very brightest LSST targets will only be accessible for detailed follow-up characterization with the largest ground-based telescopes.

There is therefore increasing interest in development of machine-learning techniques that can more fully harness the information content of the light curves themselves in order to make rapid, intelligent guesses as to the nature of the objects, and timely deploy a sensible follow-up plan that optimally exploits the available resources (including potentially AS4 resources). For example, work by Richards et al. (2012) and Parvizi et al. (2014) demonstrates that machine learning classifiers can identify variable stars (e.g., eclipsing binaries, RR Lyrae, Cepheids, etc) with good accuracy and efficiency, and Miller et al. (2015) has demonstrated that photometric variability together with colors can be used as a proxy for classifying many types of variable objects.

Ness et al (2015) have recently described "The Cannon", a data-driven model using a training set of a few hundred reference objects to obtain stellar parameters and abundances, and shown that it accurately recovers the parameters for tens of thousands of objects observed with APOGEE. A combination of this spectral modeling with light curve characterization would provide a powerful tool for analysis and classification of variable objects.

For these machine learning techniques, it is essential to have reliable training sets, i.e., large sets of benchmark objects spanning as large a range of parameter space as possible, and whose properties are determined independently. The training sets available today are largely restricted to bright objects and provide little overlap with LSST. An APOGEE/BOSS time domain survey could produce larger, more complete, deeper training sets. These observations would necessarily still be restricted in overlap with LSST transients, but would be suitable machine learning training sets where cosmic evolution is not a crucial parameter.

Additionally, a number of transients will be discovered by LSST in the very early, very faint phases, but are destined to brighten, some to magnitudes above the LSST saturation limit, and accessible to ground based follow-up surveys. Being able to predict the time evolution of transients from the very first photometric measurement would enable follow-up from the ground, including possibly early spectroscopy from moderate aperture telescopes. For many transients (e.g. supernovae) the early time behavior offers a unique and crucial insight, and an early time spectrum, together with early light curve characterization, reveals more information on the physical processes taking places than vast amounts of data at later epochs (Bernstein et al. 2013).

Since the required large training sets of spectroscopically-classified photometric variables do not exist today, it is likely that such datasets will have significant intrinsic value beyond the instrumental purpose of classifying faint LSST objects.

4. Rapid follow-up capabilities for time-domain alerts in the LSST era.

The recent NRC study ("Elmegreen report") has highlighted rapid follow-up of transient objects identified by LSST and other time-domain surveys (e.g. the Zwicky Transient Factory, ZTF) as a priority for the system of US telescopes in the next decade. The current plan is for alerts from LSST to be sent to the community within 60 seconds of being observed. In order for the 2.5-m to have a major role in *rapid* follow-up, a fiber positioner would be required, and a significant change in operations.

However, rapid transient classification is an imperfect fit for multi-object spectroscopy, as in any single 2.5-m field there will be at most a few astrophysically interesting transients that require rapid followup at any given time. While LSST will sharply increase the discovery rate, most of its events will be too faint for 2.5-m followup. In fact, near-term surveys like ZTF and ATLAS will discover transients brighter than 21st mag at rates comparable to that of LSST. We can get an order of magnitude number by looking at the SN Ia rate. SNe Ia are the most common SN type with the best-understood rates, and bright ones can be visible for months. For SNe Ia bright enough for BOSS spectroscopy (peak mag < 21), we estimate that there are about 1425 Ia (of any age) visible in the SDSS-accessible night sky above $|b| = 20$ deg at any moment. That is about 0.07 per square degree, or about 0.5 per SDSS field. One can bump the number up by a factor of a few, because there are other extragalactic (and galactic) transient classes. However, these estimates already assume perfect detection efficiency and instantaneous public transient announcements, both idealizations, so we probably come back down a factor of a few. Another concern is that depending on the age and brightness of the transient, some fraction of the transients will already have spectra from other facilities, potentially lowering the value of obtaining an additional SDSS spectrum. More generally, SN followup consumes the bulk of time domain spectroscopic followup today, so it seems like the most appropriate proxy for future observations.

Accordingly, for rapid classification of high-value transients it is likely the community will continue to seek dedicated single-object Target of Opportunity observations. The 3.5-m already has flexible, Target-of-Opportunity, observing capabilities with a suite of instruments on approximately a 15-30 minute timescale and could be used for this purpose. Whether there is an operations model that would combine the two telescopes could also be explored.

However, more complex operational models could still enable useful transient followup with the 2.5m. For slowly-evolving transients, lower-priority events, and unusual variables, rapid followup would not be required. With a fiber positioner, observations of time-varying objects could be interleaved into other surveys with fixed targets using spare fibers. A given telescope pointing would then contain objects corresponding to a range of programs, including both static science and time-domain followup. Since most fields would likely only be visited a handful of times for the static targets that use most of the fibers, scheduling the observations to maximize the value of the time-sensitive piggyback science would require some care.

If plate manufacturing or modification latency could be reduced to a week or two, slow transient followup could also be interleaved into existing programs without requiring a fiber positioner, albeit with less flexibility.

With a fiber positioner one could pre-publish planned observing locations and the collaboration could fill in targets on ancillary fibers dynamically--these could be time-domain targets if the sky coverage/cadence combination is well chosen. One way to improve the odds of having fresh transients in the fiber field is to have a dedicated imaging survey to serve as a feeder--either with dedicated hardware or through a partnership with "ZTF-2" or something similar. The idea here would be to lead the planned fiber fields by some cadence (hours? days?) so as to improve the chances of having fresh transients to include in the ancillary fibers. This might not be so hard: ZTF and ATLAS can already both survey the whole Northern sky to the relevant depths in about a night. While most fiber fields will not have any interesting transients that happen before they are observed, some will.

Finally, for transient followup, fast reduction and sharing of the data is important both to guide later followup and for priority claims. SDSS has traditionally operated in a slower mode, so some evolution of the data processing pipelines would be needed**.**

In summary, the TDA subcommittee concludes that a compelling case can be made for an AS4 time domain survey that encompasses some or many of the above ideas. As many as half of the AS4 white papers submitted in fall 2015 could potentially fit into this survey, and if time domain is explicitly mentioned in the call for letters of intent, perhaps even more ideas will be received. It would be very valuable for all of the time domain proposers to participate in a workshop to discuss how to combine their science goals in an optimized way.

The committee is particularly enthusiastic about an eventual survey strategy that would address a number of concurrent science objectives by optimizing the use of each fiber field to: obtain repeat observations of a range of scientifically interesting targets at various cadences;

benchmark training sets for machine learning; perform characterization of targets for space missions; and conduct transient followup. For example, ***one possibly unique capability would be an observing mode that has as its backbone a pre-determined list of all-sky targets for multiple science programs (e.g., TESS/PLATO precovery, multi-epoch spectroscopy of variable sources, benchmarks for machine learning, etc) but whose pointing scheduling is principally interrupt driven by the real-time rapid response needs of transient surveys such as ZTF or LSST.*** *Depending on the target density of a final selected set of science programs, an AS4 time domain survey could also potentially be combined with other proposed AS4 surveys.*