The Impact of the Astro2010 Recommendations on Variable Star Science

Corresponding Authors

Lucianne M. Walkowicz
Department of Astronomy, University of California Berkeley
lucianne@astro.berkeley.edu
phone: (510) 642–6931

Andrew C. Becker
Department of Astronomy, University of Washington
becker@astro.washington.edu
phone: (206) 685–0542

Authors

Scott F. Anderson, Department of Astronomy, University of Washington
Joshua S. Bloom, Department of Astronomy, University of California Berkeley
Leonid Georgiev, Universidad Autonoma de Mexico
Josh Grindlay, Harvard–Smithsonian Center for Astrophysics
Steve Howell, National Optical Astronomy Observatory
Knox Long, Space Telescope Science Institute
Anjum Mukadam, Department of Astronomy, University of Washington
Andrej Prša, Villanova University
Joshua Pepper, Villanova University
Arne Rau, California Institute of Technology
Branimir Sesar, Department of Astronomy, University of Washington
Nicole Silvestri, Department of Astronomy, University of Washington
Nathan Smith, Department of Astronomy, University of California Berkeley
Keivan Stassun, Vanderbilt University
Paula Szkody, Department of Astronomy, University of Washington

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Abstract

The next decade of survey astronomy has the potential to transform our knowledge of variable stars. Stellar variability underpins our knowledge of the cosmological distance ladder, and provides direct tests of stellar formation and evolution theory. Variable stars can also be used to probe the fundamental physics of gravity and degenerate material in ways that are otherwise impossible in the laboratory. The computational and engineering advances of the past decade have made large–scale, time–domain surveys an immediate reality. Some surveys proposed for the next decade promise to gather more data than in the prior cumulative history of astronomy. The actual implementation of these surveys will have broad implications for the types of science that will be enabled. We examine the design considerations for an optimal time–domain photometric survey dedicated to variable star science, including : observing cadence, wavelength coverage, photometric and astrometric accuracy, single–epoch and cumulative depth, overall sky coverage, and data access by the broader astronomical community. The best surveys must combine aspects from each of these considerations to fully realize the potential for the next decade of time–domain science.

1 Introduction

Recent surveys such as MACHO, OGLE-II and III, HAT, ASAS, SuperWASP, HIPPARCOS, and others have provided insight into the distribution of stellar variables as tracers of local structure, as well as the intrinsic nature of variability in the objects themselves. In the coming decade, the next generation of large–scale surveys will build on these discoveries as well as raise new questions. We argue that an optical, time–domain survey lies at the critical intersection of feasibility, science return, and discovery potential if the data can be shared with the community and its vast diversity of domain experts. All–sky (or all–available–sky) surveys allow us to test in an unbiased manner the power–spectrum distribution of matter in the Galaxy and in the Universe. Through the production of very large samples of known variable types, these surveys will enable statistical studies of the ensemble to definitively characterize the class boundaries and find outliers from the mean (Covey et al., 2007). These surveys will also lead to the discovery of theoretically predicted populations that have not yet been observed (eg. pulsating brown dwarfs; Palla & Baraffe, 2005) as well as systems found in unique configurations (eg. eclipsing AM Canum Venaticorum systems; Anderson et al., 2005). A prime example of this paradigm is the Sloan Digital Sky Survey (SDSS), a single–epoch photometric survey of more than 10^4 square degrees determined to have the highest recent impact in astronomy based on a citation analysis of papers by Madrid & Macchetto (2009). A time–domain survey with immediate public data access is the next logical step in the evolution of astrophysical surveys, and will have a transformative impact across all disciplines of astronomy. For a full overview of recent results from stellar variability surveys, we refer the reader to the review by Eyer & Mowlavi (2008). In this white paper, we highlight high–impact projects that will be made possible by large–scale time–resolved samples of known variable classes.

1.1 Calibrating Cosmic Distance: Cepheids, RR Lyrae and Miras

Pulsating stars are the preeminent distance indicators, both as local rungs in the cosmic distance ladder and as tomographic tools to study the 3-D structure of the Galaxy. With RR Lyrae and Cepheid variables, uncertainties in distances measurements coupled with unknown dust and metallicity correc-

tions translate directly into uncertainties in cosmological parameters (Bono, 2003; Tammann et al., 2008). Advances in image subtraction techniques applied to repeated deep imaging have extended the range to which these stars may be detected in external galaxies. Ensembles of these stars derived from a range of star formation histories will enable solutions for the metallicity dependency of their period–luminosity relationships, making them more precise distance indicators. The superior depth provided by new endeavors like LSST (`http://www.lsst.org`) will make statistically significant samples of extragalactic variables a reality.

Beyond the optical, equivalently deep infrared observations (e.g. SASIR; `http://www.sasir.org`) would allow for a precise calibration of the period–luminosity relations at infrared wavelengths, skirting issues of dust extinction (and in combination with optical observations allow the construction of a wide–field dust map of unprecedented spatial precision). In turn, AO-enabled 30 meter telescopes would then be able to measure precise distances well-beyond the local group and finally fix the rungs of the cosmic distance ladder out to ~ 25 Mpc.

These new observations will also improve our understanding of the structure and history of our own Galaxy: RR Lyrae are essential tracers of structure and metallicity in the Milky Way (Smith, 1995). SDSS detected RR Lyrae to distances of $\sim$100 kpc (Sesar et al., 2007), uncovering halo substructure through clumps in the RR Lyrae spatial distribution. LSST will detect RR Lyrae to distances of $\sim$400 kpc, providing extensive tests of hierarchical galaxy formation models (e.g. Bullock et al., 2001).

Mira variables are the most luminous of potential distance indicators, but their use has been observationally impractical due to their extremely long periods (hundreds of days). However, their luminosities give the Mira population great potential as a cosmic distance indicator, bridging the distances where vast amounts of stellar variables are found, and where vast numbers of Type Ia Supernova are found. **Finally, we mention that the ability to detect variables in external galaxies opens the window to the detections of extraordinarily rare, one–in–a–galaxy, phenomena.**

1.2 Luminous Blue Variables and Cool Supergiants

The scarcity of high mass stars poses a serious challenge to our understanding of stellar evolution atop the HR diagram. As O–type stars evolve off the Main Sequence their violent death throes can be characterized by extreme mass loss and explosive outbursts, which are short–lived and possibly intermittent. There are only a handful of nearby massive stars that are caught in this phase at any given time (as in the case of η Car), which makes it very difficult to connect distant explosions (supernovae and GRBs) to their underlying stellar populations.

The improved depth and breadth of proposed surveys will make these extremely luminous stars accessible in other galaxies, allowing the community to continue the expand on the early work of Hubble & Sandage (1953) and Tammann & Sandage (1968). Time–resolved observations of variability in this new sample will quantify the statistical distribution of time–dependent mass–loss rate, luminosity, radiated energy, total mass ejected, duration of outbursts, time between outbursts, and connections to the pre–outburst stars. New observations will inform models of massive star evolution, including its dependence on metallicity, providing prescriptions for the time–dependent properties mentioned above so that they can be included in stellar evolution codes in a meaningful way. In a complementary fashion, further study of these stars will also improve our understanding of galactic feedback and enrichment of the interstellar medium.

Another open question regards the true nature of core collapse supernova (CCSN) progenitors.

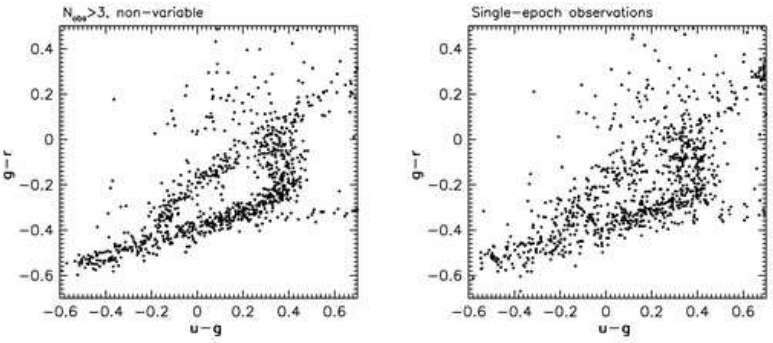

Figure 1: SDSS color–color diagram for objects near the white dwarf cooling sequence. The *right* panel shows the colors for all sources seen to be non–variable over many epochs, but only shows their photometric measurements from one epoch. The *left* panel shows the mean colors for these objects over all epochs, and resolves cooling sequences much less apparent in the single epoch photometry. Adapted from Figure 24 of Ivezić et al. (2007).

A large sample of evolved massive stars will propel our understanding of the diversity of CCSN progenitors. **Among the large sample of luminous stars monitored in nearby galaxies, some may explode while they are being monitored**. This will provide not only an estimate of the star's pre–explosion luminosity and temperature, but also its variability and potential instability in the final years of its life. It is also possible that stellar population studies of the surrounding field stars can constrain the local star formation history, and thus constrain the delay time between star formation and core collapse.

1.3 Galactic Chronometers: Pulsating White Dwarfs

Isolated white dwarf variables are found in four distinct instability strips located in different temperature regimes. All of the white dwarf variables exhibit nonradial gravity–mode pulsations, and most of these pulsators are multi–mode, showing at least a few modes at the same time. Differences in pulsation amongst hydrogen–atmosphere white dwarfs are predominantly affected by differences in temperature, as these stars are otherwise very homogeneous. As white dwarfs are simply radiating away leftover thermal energy, the luminosity of a given white dwarf is a straightforward function of age. A large sample of white dwarfs will thus allow calibration of the white dwarf cooling curves.

The observed pulsational periods are tens to thousands of seconds, with amplitudes as large as 10% and diminishing in amplitude as the stars reach the edges of their instability strip. There are four known white dwarf instability strips, although their boundaries are not well defined. These come from the Hydrogen atmosphere (DA), Helium atmosphere (DB), hot (DO), and recently discovered Carbon atmosphere (Fontaine et al., 2009) white dwarfs pulsators. A survey observing these stars once a night may not entirely resolve the pulsational period. However, repeat measurements will uncover those stars that exhibit a scatter in their lightcurves larger than the measurement uncertainties. These ensembles of stars can then be used to experimentally *define* the extent of the white dwarf instability sequences. A similar illustrative experiment was carried out by Ivezić et al. (2007), using data from SDSS repeat observations. Figure 1 shows the colors of non–variable ($\sigma_g < 0.05; \sigma_r < 0.05$) objects near the white dwarf cooling sequences. The rightmost panel shows single–epoch colors taken from SDSS DR5. The left panel shows the averaged colors of the objects over ~ 10 epochs. Multiple sequences are apparent which were not evident in the single–epoch photometry, two of which correspond to the cooling curves of H and He white dwarfs (Bergeron et al., 1995). **These are fundamental tests of degenerate matter that cannot be replicated in the lab.** This includes constraints on exotic particles such as axions and plasmon neutrinos (Kim, 2007).

1.4 Close and Interacting Binaries

New surveys will also allow for the first robust, volume–limited population census of stellar remnants within our Galaxy. Of these remnants, the most numerous and easiest to study observationally are the interacting white dwarf binaries. These systems include X-ray binaries and symbiotic stars (for more massive stars), cataclysmic variables (CVs – including novae, dwarf novae and novalikes) and ultimately, the double–degenerate AM CVn systems (Tutukov & Yungelson 1996) and Ultra-compact X-ray binaries (Nelemans et al. 2006).

As a large fraction of stars are binaries, it is important to understand the effects of binary membership on stellar evolution. Binary interaction also alters the stellar evolution process in many ways that can result in spectacular transient and variable phenomena. Faint, wide surveys will find binaries at greater distances, with lower mass companions and lower mass transfer rates than previously possible. A time–domain study of these systems will allow us to characterize the patterns of accretion across the spectrum of $\dot{M}$ in a systematic fashion. The majority of CVs in the Galaxy are predicted to have low mass–transfer rates and thus be intrinsically faint ($22 < V < 25$; Howell et al., 2001; Politano et al., 1998) just below the limiting magnitude of recent all–sky surveys such as SDSS but distinguishable by both their colors and intrinsic variability in next–generation surveys. Detection of this theoretically predicted population will provide fundamental tests of many aspects of stellar evolution – how stars form into giants and super–giants, how mass loss and core evolution proceeds as the stars evolve into white dwarfs, and the process of angular momentum loss – ending with the majority population of white dwarf binaries. **Direct detection of CVs across the spectrum of mass transfer rate, especially detecting the faint majority population, will help us to understand the diversity seen in cosmological Type Ia supernovae (Filippenko, 2005) by observing the diversity in their progenitor Galactic systems.** Finally, the space density and orbital period distribution of detected AM CVn are key ingredients in understanding the gravitational wave sky expected to be unveiled in the next decade (Nelemans et al., 2004).

1.5 Additional Science Topics

We enumerate other unique science that is enabled by a broad time–domain survey, and that may be emphasized more thoroughly in other white papers. This includes :

- An unbiased measurement of the period–amplitude diagram of stellar variability;
- The frequency and amplitude of flares on M–dwarf stars, which affects their astrobiological viability as hosts for habitable worlds;
- The measurement of the masses of isolated objects using gravitational microlensing. This technique is sensitive to planetary–mass to black hole–mass objects, and is one channel to finding exotic types of compact objects;
- Understanding the diversity of cosmological transients by characterizing the foreground of Galactic phenomena.

Finally, we emphasize the strength of time–domain surveys : **repeat observations enable both the identification of periodic, non-periodic, and new classes of variable source as well as more accurate properties for non-variable sources.**

2 Technical Feasibility : Survey Design Considerations

In the following section, we discuss the design considerations for an optimal time–domain photometric survey dedicated to variable star science, including observing cadence, wavelength coverage, photometric and astrometric accuracy, and data access by the broader astronomical community.

2.1 Photometric Accuracy

The internal photometric calibration of a survey reflects the degree to which it can detect variability. The newest frontiers are enabled by survey–scale photometry repeatable at the 1% level or below, which enables novel science such as estimating the ages of stars through their rotation period (where the variability comes from star spots) or detecting solar–type oscillations on other stars (Gilliland et al., 1993). The limits on internal calibration come from a combination of irreducible random noise, and systematic effects that need to be minimized in the experimental design. Recent optical wide–field ground–based surveys have achieved the benchmark of $\sim 1\%$ repeatability in photometric measurements (Ivezić et al., 2007). The fundamental limitations to this number come from uncertain calibration of the instruments and from the uncertain knowledge of the instantaneous transmission profile of the atmosphere, which causes variations in the effective filter of the system. Space–based observations avoid many of these issues, and with careful metrology can reach the photon noise limit.

All known pulsating variables with the exception of white dwarfs have $M_V < +2.5$, primarily due to observational selection effects in areal coverage, limiting magnitude, observed sample size, photometric precision, and time coverage. An expansion of capability in each of these areas will greatly increase the discovery space even for normal pulsators. Howell (2008) discusses the relationship between the detectable variable fraction and the photometric precision of a given survey, citing an exponential increase in the fraction of observed variable sources as a function of improved photometric precision. For a survey with internal calibration of 0.005 magnitudes, approximately 12% of all sources should show signs of variability. For a survey with internal calibration of 0.001 magnitudes, $\sim 50\%$ of objects should show variability. **Internal photometric accuracy is clearly a proxy for how much science can be gleaned from the data, and should be optimized at high priority.**

2.2 Astrometric Accuracy

While not addressed in previous section, fundamental science can be done using the *spatial* variability of stars. The astrometric accuracy of a survey impacts its ability to measure parallaxes and proper motions. Parallaxes in particular set the foundation for almost all astronomical measurements, being the only direct distance measure, allowing the measurement of intrinsic stellar luminosities, and measuring three–dimensional spatial structure. From the ground, atmospheric effects dominate astrometric accuracy for the bright sources, setting a systematic floor of approximately 10 milli–arcseconds (mas) per visit on spatial scales of arcminutes. From space, the PSF sets the limit of astrometric accuracy. Repeat observations of objects will average over these uncorrelated systematic effects and improve overall astrometric accuracy. In particular, the precision of parallax measurements improves with time (scaling as $t^{-1/2}$) by building up repeated observations of the parallax signal. Proper motion precision improves with time ($t^{-3/2}$) by allowing the proper motion vector to grow in amplitude. Thus long duration surveys are desirable in this regard.

2.3 Sampling Window in Time

The cadence at which a survey revisits a given object defines the timescales at which the survey is sensitive to its variability. For short, periodic variability a general survey is unlikely to Nyquist sample the full cycle. However, under the assumption of stability, sampling the signal over many cycles can lead to its period and shape recovery with little difficulty aside from sampling aliases. To address this latter issue, a "rolling cadence" with revisits at many timescales will help to remove sampling aliases, as well as to fully explore the timescales at which variability may be found.

Variability at short timescales is a regime that has been undersampled by modern surveys. The vast phenomenology known to exist there, from M–dwarf flares to optically bright Gamma Ray Bursts, have yet to be addressed in an unbiased manner. In the next decade surveys will uncover numerous instances of these phenomena, $\sim$30 per day per square degree for M–dwarf flares (Kowalski et al. 2009). Of requisite need is an initiative by the surveys to release their data to the community on a timescale commensurate with, in fact shorter than, the phenomenological timescale to trigger follow–up and study by the community.

The overall length of the survey also impacts our ability to characterize an object's variability. This statement applies equally well to variability on timescales longer than the survey's lifetime, as well as to exploring variations within shorter timescale phenomena, such as period evolution in eclipsing binary systems and in pulsating variable stars. Although space–based surveys may provide certain other observational advantages, the harsh environs of space and the difficulty of hardware maintenance ultimately limits their lifespan.

2.4 Sampling Window in Wavelength

Color information, when combined with variability amplitude and timescale, is an essential ingredient in successful object classification (Sesar et al., 2007). The choice of wavelength sampling, and in particular cadence in a given filter, strongly affects the science return possible from a given survey. Different wavelength ranges often trace fundamentally different physical processes. For example, cataclysmic variables that possess accretion disks display their greatest variability in the blue, but magnetic CVs ("polars") are most variable in the red due to cyclotron emission.

Because of opacity in the near–ultraviolet, u–band observations are powerful discriminators of metallicity. In addition, many transient phenomena (such as M dwarf flares) have their highest contrast in the blue. In any ground–based survey, however, u–band observations are difficult due to scattering by the Earth's atmosphere. At the other extreme, infrared observations are powerful means to discover the vast numbers of our M, L, and T–dwarf neighbors, as evidenced by 2MASS observations (Reid et al., 2008). Additionally, the time–domain is essentially unexplored in the infrared. Eclipsing M–dwarf systems should be found in abundance along with other interesting, intrinsically red, systems like the young stellar objects KH-15D (Winn et al., 2003).

2.5 Outreach and Data Access

A final consideration concerns the public access to, and timely release of, the survey data. It is highly unlikely that the survey teams will be able to exhaustively mine their data for variability science. Surveys that commit to enabling data access by the entire astronomical community therefore maximize the overall scientific gains. For time–domain science in particular, anything less than nearly real–time

release of the data will blunt the potential science impact of the observations. Without real–time data reduction and dissemination, the recognition and study of short timescale, transient phenomena is not likely to be achieved.

A commitment to real–time and data–release community access will leverage the considerable investment already made into standards to communicate such information efficiently, including development efforts of the Virtual Observatory and the VOEvent infrastructure. Such an integration will enable science far beyond the members of the survey teams. The entire astronomical community will benefit, from professional astronomers supervising the next–generation of autonomous follow–up telescopes (Bloom et al., 2006; Hidas et al., 2008) to amateur astronomers curious to take a peek at the newest transient event. Access to the same survey–quality data stream will both broaden and strengthen the community.

On similar footing is the degree of Education and Public Outreach proposed by each survey. The educational opportunities available with such large time–domain datasets cannot be overstated. Surveys committing to, for example, providing a feed to Sky in Google Earth ("Google Sky") are enabling K–12 science teachers to communicate daily the concept of our varying Universe. The ideal survey will also be active in outreach by participating in initiatives such as NSF's Partnerships in Astronomy & Astrophysics Research and Education (PAARE) and the DOE / NSF Faculty and Student Teams (FaST) program. We argue strongly that this is an attribute that should not be overlooked when ranking proposed programs.

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