The Variable Sky

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1 Introduction

A top-down characterization of variability in stars and galaxies allows us to predict the rates of discovery and the total numbers of variable targets that will be detected in deep synoptic surveys. The goal is to reduce the uncertainties from more than an order of magnitude to less than or of order 2×. These numbers may be useful for estimating the scale of alert distribution and characterization tasks, and the scope of the demand for target-of-opportunity follow-up.

2 Synoptic Survey Alerts and the NOAO Variable Sky Project

One of the unique products of a synoptic (here understood as repeating) survey is the production of alerts on detection of variable targets. For some such targets, rapid follow-up will be desired, which will be enabled by immediate publication. The Large Synoptic Survey Telescope (LSST) will publish alerts on all targets which show variation from a fiducial measurement, and will publish them within 60 seconds [6]. For a survey devised for its high data throughput, this suggests a challenging computational task (of particular concern to the project) and a heavy demand for follow-up facilities (of special interest to our observatory). A Google search shows estimated LSST alert rates in the range 5000 to 2,000,000 per night, and while these may involve varying definitions and assumptions, the large range and the lack of documentation is a concern.

The NOAO Variable Sky project, developed by the authors, addresses the alert rates expected for synoptic surveys. This paper collects summary results for LSST for the high latitude sky. The high latitude sky will be the hunting ground for faint, rare, extragalactic sources, and for this part of the sky, contamination by galactic variable stars will be low. Details will be published elsewhere.

3 Finding the Needle in the Haystack

Rapid alert publication supports two distinct event types—those which are known or immediately identified, and those which are unexpected or not yet identified. An automated classifier, commonly called a Broker [2], can be used to filter an alert stream in order to select useful events. However, if the alert rate is high, then even a small mis-classification rate could easily obscure or delay rare discoveries. In this context, it is important to distinguish between discovery alerts and repeat observation alerts. Eventually it will be useful to dig deeper and determine the fraction of discovery alerts that actually have sufficient archival information (as non-variable sources) to support classification and thus implicitly to estimate the alert rate for which there is no such data.

With this preface we describe below the types of variable and transient sources considered, based on estimates of which source types can be expected to dominate the alert stream.

4 Variable Star Discovery Rate per Night

A bottom-up enumeration of all variable star types did not work well, and so we took a top-down approach. The Kepler survey was used to characterize the variability of the most numerous stellar spectral classes, in terms of variability probability distribution functions as a function of temperature and (for the cooler stars) of luminosity. These probability functons were then applied to a simulated star catalog generated with the Besancon Galaxy synthesis model [10], giving a probability of variability vs amplitude for every star in the catalog. Detection limits from an LSST exposure calculator [4] were used to determine the detectability at the 5-σ level for every star, and the probabilities summed to predict the number of detectable variable stars. This was carried out for samples in and near the Galactic plane, and for an arc through the south celestial pole.

In Figure 1, the discovery rate for variable stars is shown on a per-night basis, integrated over the high latitude sky (taken as $|l| > 20$ degrees). The discovery rate is based on the observed statistics of variability, and how many new variables will be detected based on the length of the observing sequence.

Guided by the LSST criterion for issuing alerts, new alerts will be issued for most variable stars most times that they are observed. Thus these detections all contribute to the alert rate, also shown in Figure 1. However, as known variables, they will have a history and existing characterization, greatly reducing the data distribution load on the alert system, the characterizing burden on the Broker, and presumably the follow-up effort required for classification.

5 AGN Discovery Rate per Night

A similar approach was employed in the study of AGN variability and discovery rates. However, here the available data on variability are far less numerous and homogeneous. A luminosity function for galaxies [8] was combined with the additional assumptions that 2.5% of all galaxies have AGNs [5], and that all AGNs are variable at the $\sim$ 10 mmag level [3] or more. A study of AGN variability [5] provided a variability probability vs amplitude function. The most poorly determined quantity is the probability distribution of variability time scales. In the example shown here, a characteristic time constant of 6 months was assumed, which determines the slope in the discovery rate, though a more complete description might allow for a range of time scales. As with stars, it is assumed that once variation has become evident, that AGN will continue to generate alerts after the discovery, hence contribute to on-going alert rate. In Figure 1, the AGN alert rate is assumed equal to the initial AGN discovery rate, since there is insufficient statistical characterization for a more elaborate model.

6 Variable QSO Discoveries per Night

The surface density of QSOs [9] and the predicted cumulative distribution of magnitude differences [7] are used to predict the discovery rate. The discovery rate for QSO's is also shown in Figure 1 in the same way as for AGNs. The increase with time of the QSO variability amplitude (described by the structure function) tends to flatten the discovery rate. The time constant is not well characterized, so the discovery rate is shown here as flat though it will begin to decline after a few years.

7 LSST Alert Rate vs. Discovery Rates

Figure 1 shows an estimated high latitude alert rate of $\simeq 10^5$/night. This would be an ominous number if it were necessary to analyze this many new targets nightly. However, as shown in Figure 1, we predict that the number of discovered sources of the most abundant and familiar types will be more nearly $\simeq 1000$/night. Furthermore, most of the QSOs and AGNs, when detected as variables, will already have long time series giving good colors, and most likely a history of sub-5σ variability, and these two pieces of evidence will support a high confidence of classification. These targets aside, SNe will be among the most numerous discoveries, and these will be readily identified with a combination of history and association to galaxies.

We do not include here cataclysmic variables, owing to lack of good luminosity functions and variability probability information for the more numerous, evolved CVs. As we will discuss elsewhere, if the number density of detectable CVs is as large as permitted by stellar population estimates, CV discoveries could compete with QSOs. However, most CVs will also be identifiable from archival colors and low-level variability.

In order to determine the discovery rate of variable sources which cannot be immediately classified from archival data, we note that for such targets it will be essential to obtain immediate forced photometry on the target location, since the observational history below the catalog brightness cutoff will be necessary, and probably sufficient, for characterizing most of the faintest targets.

Of course a residual number of alerts will be generated by targets which have been fainter than the forced photometry stacked limit prior to discovery - these will number among the few sources which are initially both anonymous and (individually at least) unforeseeable. The expected counts for cool, flaring dwarfs, AGNs and QSOs brightening from below to above the detection limit can be estimated by extension of the analysis described above, but this exercise is deferred to a future study.

8 Number of objects in the LSST transient and variable catalog

The integral of the discovery rates gives a good measure of the size of the LSST transient and variable catalog, which is predicted to trend towards a little less than 10^7 high latitude sources over the 10 years survey.

9 What about the Galactic plane?

The study produced a map of variable number densities on the sky. The expected number of variable stars in the LSST-observed plane is $\simeq 2.5$ orders of magnitude larger than in the high latitude sky. However, it is not correct to multiply the star discovery rate in Figure 1 by this factor, as LSST may spend less time in the plane than in the high latitudes. Furthermore, the analysis above assumes photon- and calibration-limited detectability of variability. In the galactic plane, crowding may set the limit significantly above this. Finally, the trigger level for variability alerts is a selectable parameter, and it is not likely to be set at a level that overwhelms feasible processing.

10 Another Synoptic Survey – GAIA

Extending this analysis to the European Space Agency astrometric mission GAIA shows the perhaps unexpected result that in spite of an enormous difference in telescope apertures, GAIA and LSST will detect essentially the same numbers of variable

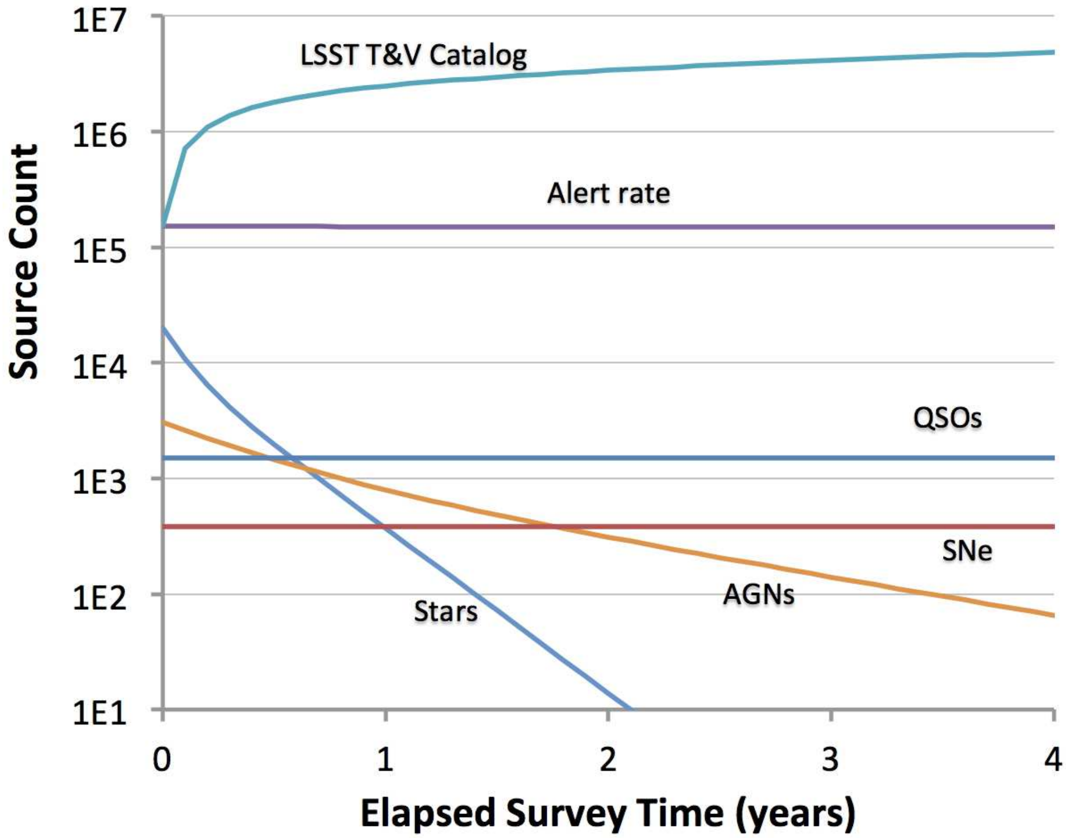

Figure 1: The LSST high latitude sky: discovery rates (per night) for stars, AGNs, SNe, and QSO's; alert rates (per night) for all of these source types combined; and transient and variable catalog sizes (total expected number of objects).

stars. The difference is that, while the GAIA survey will stop at g=20, it will reach lower levels of variability, thanks to the better photometry possible above the atmosphere. Approximately 90% of the variables detected by GAIA will have amplitudes of order 10 mmag or less.

We have presented this project at several conferences, and we are grateful for the feedback received. A longer version of this work, with details of assumptions and calculations, will be submitted for publication.

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Despite the importance of variability, the variable optical sky remains largely unex-plored and poorly quantied, especially at the faint end. To what degree dierent variableÂ To address these questions, several contemporary projects aimed at regular monitoring of the optical sky were started. Some of the more prominent surveys in terms of the sky coverage, depth, and cadence are: â€¢ The Faint Sky Variability Survey (Groot et al. The NOAO variable-sky project. In E. Griffin, R. J. Hanisch, & R. L. Seaman (Eds.), New Horizons in Time-Domain Astronomy (S285 ed., pp. 361-363). (Proceedings of the International Astronomical Union; Vol. 7, No. S285). https://doi.org/10.1017/S174392131200107X. The NOAO variable-sky project. / Matheson, T.; Blum, R.; Jannuzi, B.; Lauer, T.; Norman, D.; Olsen, K.; Ridgway, S.; Saha, A.; Shaw, R.; Walker, A. New Horizons in Time-Domain Astronomy. ed. / The Variable and Transient Sky Seen by. Fermi. Julie McEnery NASA/GSFC. 1. A combination of wide field of view and survey mode enabled Fermi to explore the high energy gamma-ray sky on timescales from milliseconds to years. 2. The Variable Gamma-ray Sky. 3. The flaring and variable sky.Â â€¢ Some of this energy fuels a jet. â€¢ Multiwavelength observations of blazar variability provides key information on the nature of the jets. 5. PKS 1830-211 - A Gravitational Lens.