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Cadence Note: Cadence impacts on reliable classification of standard-candle variable stars, including detection of amplitude period, phase modulation effects (e.g., Blazhko effect)

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1. INTRODUCTION

The Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST) will carry out its science goal of "Mapping the Milky Way" through both astrometry and photometry, with a single-exposure depth of $r{\sim}24.7$ and an anticipated baseline of 10 years. This will enable LSST to access the Milky Way's old halo not only deeper, but also with a longer baseline and better cadence than e.g. PS1 3π (Chambers et al. 2016), making this survey ideal to study populations of variable stars such as RR Lyrae (Hernitschek et al. 2016; Sesar et al. 2017a).

As members of the Transients and Variable Stars (TVS) Classification group, we focus on the specific science case of detecting period/ phase shift effects, so-called Blazhko effect (Blazhko 1907), of RR Lyrae stars. So far, due to depth and cadence of typical all-sky surveys, it was nearly impossible to study this effect on a larger sample. Surveys such as PS1 3π with relatively few observations over a moderately long baseline allowed only for fitting the period and phase of RR Lyrae stars while integrating over the complete survey length, thus not giving any information regarding whether the period and/or phase of the light curve might have changed during the survey. On the other hand, surveys specialized for detecting slightly changing light curves due to very finely sampled cadence (such as TESS, see Ricker et al. 2015) usually have a relatively small footprint. LSST's cadence and depth, however, will allow for studying variable stars in the Milky Way's old halo in a way that makes population studies possible.

2. SCIENCE CASES

Pulsating stars of the RR Lyrae type have been studied for over a century now, as they play an important role in distance estimation as well as in studying the old halo content, such as globular clusters and stellar streams, of our Milky Way. RR Lyrae stars serve as relatively easily detectable standard candles, enabling the calculation of distances from PLZ (period, luminosity, metallicity) relationships. Depending on their light-curve characteristics, RR Lyrae stars are divided into subclasses. The RRab stars, pulsating in the fundamental radial mode, show high-amplitude, skewed non-sinusoidal light curves. RRc stars, in contrast, pulste in the radial first overtone mode and show a nearly sinusiodal light curve with smaller amplitudes than RRab stars. RRd stars pulsate in both modes simultaneously.

The Blazhko effect, first observed by S. Blazhko in 1907 in the star RW Draconis (Blazhko 1907), is a modulation of period, phase and amplitude in RR Lyrae stars. The typical pulsation period of an RR Lyrae star is 0.2 - 1.1 days with a 0.5 - 1 mag amplitude, whereas the modulation due to the Blazhko effect is on timescales from weeks to months, and its amplitude is a few tenths of magitudes smaller. The Blazhko effect is observed for about 20 - 30 % of the RRab stars (Szeidl 1988; Moskalik & Poretti 2003) and for less than 5 % of the RRc stars.

The physics behind the Blazhko effect is still under discussion. Among the three primary hypothesis, the first (resonance model) sees the cause of the modulation in a nonlinear resonance among the fundamental or the first-overtone pulsation mode and a higher mode. The second (magnetic model) sees the cause of the modulation in the magnetic field being inclined to the rotational axis of the star, thus deforming the main radial mode. The third model assumes cycles occurring in the convection as cause for the modulations. The cadence, depth and large footprint of LSST will allow us to address questions such as how frequent the Blazhko effect is, and in addition will allow us to carry out population studies on stars showing these modulation effects. Such studies then can shed more light on the question of underlying physical processes driving the Blazhko effect. Also, as using RR Lyrae stars as standard candles, determining correct periods is crucial for calculating distances. Better understanding the impact of the Blazhko effect,

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and taking it into account when calculating distances, will improve our ability to study the halo population of our Milky Way.

3. THE METRIC

We have developed a metric `PeriodicStarModulationMetric` to evaluate the feasibility of recovering light-curve modulation in RR Lyrae stars, such as caused by the Blazhko effect. While our primary purpose is studying the detection of the Blazhko effect, this metric not solely aims at that purpose, but at evaluating variable star light curves from short time intervals in general. We evaluate our metric at OpSim 1.7 databases `baseline_nexp2_v1.7_10yrs.db` (baseline), `rolling_scale0.2_nslice2_v1.7_10yrs.db` (rolling cadence) and `pair_times_55_v1.7_10yrs.db` (pair times cadence), see the OpSim1.7 Summary Information Document[1].

The goal of our metric is to calculate the fraction of recovered RRab stars based on the light curve length (time interval within 2 years of LSST) and distance modulus. The metric is based on the `sims_maf_contrib` `PeriodicStarMetric` metric, which was modified in a way to reproduce attempts to identify a change in period, phase or amplitude in RR Lyrae stars. We have not implemented this modulation in the curve itself, as the modulation can take very different forms. Instead, we investigate how well we can identify period, phase or amplitude from a variable star's light curve on rather short baselines (15, 20, 30, 50 days). This attempt is also useful for other purposes, i.e. if we want to test whether we can just recover period, phase and amplitude from short baselines at all, without necessarily having in mind to look for light-curve modulations.

Like in `PeriodicStarMetric`, the light curve of an RR Lyrae star, or a periodic star in general, is approximated as a simple sin wave. (A future version might make use of light-curve templates to generate light curves, see e.g. the RRab and RRc light curves from Sesar (2012).) Instead of evaluating the complete light curve at once, we split light curves into time intervals. We then measure the fraction of light curves whose parameters are recovered correctly (within a given tolerance) from those time intervals. Two other modifications we introduced for the `PeriodicStarModulationMetric` are: In contrast to `PeriodicStarMetric`, we allow for a random phase offset to mimic observation starting at random phase. Also, we vary the periods and amplitudes within +/- 10 % to allow for a more realistic sample of variable stars.

To test whether the parameters amplitude, period and phase offset of a simulated light curve can be correctly recovered, we run a simple `curve_fit` (`scipy.optimize`).

We evaluate our metric for different values of the distance modulus (17.0, 18.0, 19.0, 20.0, 21.0, 22.0) as well as different length of time intervals (15, 20, 30, 50 days) on sin-wave light-curves with amplitudes and periods typical for RRab and RRc stars.

Code and figures can be found in our github repository, `https://github.com/ninahernitschek/LSST_cadencenote`.

4. ANALSIS OF RESULTS

We evaluate our metric on simulated 2-year light curves for OpSim 1.7 databases `baseline_nexp2_v1.7_10yrs.db` (baseline), `rolling_scale0.2_nslice2_v1.7_10yrs.db` (rolling cadence) and `pair_times_55_v1.7_10yrs.db` (pair times cadence). Light curves were simulated both for RRab and RRc stars. As the results are extremely similar, we focus on the RRab results, see Fig. 1. A similar graphic for RRc stars can be found in our repository.

4.1. *LSST Baseline Survey Results*

In Fig. 1, we plot the area (in 1000s of square degrees) for which a given fraction of RRab stars can be correctly detected, i.e. the light curve parameters retrieved within the allowed tolerances. We do this for time intervals of 15 to 50 days, and the distance modulus spanning 17 to 22.

As expected, the area over which a relevant fraction of RRab and RRc stars can be correctly recovered from such short time intervals drops significantly for a distance modulus > 20. For a distance modulus up to 19, for more than half of the survey footprint more than half of the light curves can be fit correctly using time intervals of 30 days. For a distance modulus of 21, we have to move to a time interval of 50 days to get a correct fit for 10 %.

Also, as expected, we find an increase of the recovery rate over time interval length. Here we want to highlight that even for a distance modulus of 20, over half of the survey footprint more than 30 % of the light curves can be recovered correctly from a time interval of 50 days. For a lower distance modulus, the same recovery rate can be achieved for

[1] `https://github.com/lsst-pst/survey_strategy/blob/master/fbs_1.7/SummaryInfo.ipynb`

time intervals from 15 - 20 days. As the modulation due to the Blazhko effect happens on timescales from weeks to months, using a time interval larger than 20 days is reasonable.

As we are especially interested in RR Lyrae stars in the outer halo, we are dealing with a distance modulus > 19.

We now take a look at the influence of different survey strategy choices.

4.2. *Figures of Merit for Different Survey Strategy Choices*

For the rolling cadence (evaluated only on `rolling_scale0.2_nslice2_v1.7_10yrs.db`), we find a sometimes (depending on distance modulus and time interval) slightly higher, sometimes slightly lower fraction of recovered light curves per area than for the baseline survey, but always less recovered light curves per area than for the the pair times cadence (`pair_times_55_v1.7_10yrs.db`).

In this comparison, we thus see as slight advantage of the pair times cadence over the other cadences tested.

Varying the pair time changes the overall number of filter changes per night, so longer pair times (55 minutes in our case) result in more visits overall in the survey. In addition, this matches better the typical time scale of RR Lyrae light curves: The standard baseline attempts pairs at 22 minutes, whereas here we have chosen 55 minutes as timeline over which RR Lyrae star vary significantly.

The survey strategy of a rolling cadence means that some parts of the sky receive a higher number of visits during an 'on' season, followed by a lower number of visits during an 'off' season, while during the first as well as the last year and half, the sky is covered uniformly as normal. We have so far not tested the influence of cadence on a full 10-year survey, but assume from our tests so far that the influence of a rolling cadence might be worse.

5. ANSWERS TO QUESTIONS REGARDING SURVEY FOOTPRINT

Q1: Are there any science drivers that would strongly argue for, or against, increasing the WFD footprint from 18,000 sq. deg. to 20,000 sq.deg.? Note that the resulting number of visits per pointing would drop by about 10%. If available, please mention specific simulated cadences, and specific metrics, that support your answer.

(No response.)

Q2: Assuming that current system performance estimates will hold up, we plan to utilize the additional observing time (which may be as much as 10% of the survey observing time) for visits for the mini-surveys and the DDFs (with an implicit assumption that the main WFD survey meeting SRD requirements will always be the first priority). What is the best scientific use of this time? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

Here we refer to our LSST survey white paper (co-author Nina Hernitschek) *Mini-survey of the northern sky to Dec < +30, LSST Survey White Paper* (Capak et al. 2018).

Q3: Are there any science drivers that would strongly argue for, or against, the proposal to change the u band exposure from 2×15 sec to 1×50 sec? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

Detecting and characterizing RR Lyrae star in the old Milky Way's halo would benefit from an increased exposure time of 1×50 sec.

Q4: Are there any science drivers that would strongly argue for, or against, further changes in observing time allocation per band (e.g., skewed much more towards the blue or the red side of the spectrum)? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

(No response.)

Q5: Are there any science drivers that would strongly argue for, or against, obtained two visits in a pair in the same (or different) filter? Or the benefits or drawbacks of dedicating a portion of each night to obtaining a third (triplet) visit? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

Observations in different filters are helpful for classification based on colors, for example to first identify RR Lyrae stars (and other standard candles) when light curves are too sparse to calculate periods. However, our attempt of getting precise periods, phases and amplitudes will benefit from having more observations in the same filter. As shown above, the simulation wit a pair-spacing cadence of 55 days (`pair_times_55_v1.7_10yrs.db`) improves the recovery rate of RR Lyrae periods, phases and amplitudes from short-time light curves, as there is no significant variability on e.g. the 20-minute baseline.

Likely visit pairs more widely spaces would improve the ability to recover those light-curve parameters.

Q6: Are there any science drivers that would strongly argue for, or against, the rolling cadence scenario? Or for or against varying the season length? Or for or against the AltSched N/S nightly pattern of visits? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

The rolling cadence could benefit variable stars investigation in the Galactic Plane by providing higher-cadence lightcurves. However, for variability analysis of RR Lyrae stars, we are looking for high-latitude objects in the old Milky Way's halo. Our simulations for the rolling cadence have shown that the results are worse than for the baseline survey strategy.

This also agrees with other more general analysis showing the coverage of one-day timescales (see Cadence Note by Eric C. Bellm and Michael Coughlin): They find that the `rolling_scale` and `alt_roll` simulations have very poor (sub-percent) coverage of one-day timescales, the `rolling_nm_scale1.0_nslice2` result is close to the `baseline`, and `rolling_nm_scale0.90_nslice3_fpw0.9_nrw1.0` approaches the `pair_times_55` simulation in its effective timescale coverage.

Q7: Are there any science drivers pushing for or against particular dithering patterns (either rotational dithers or translational dithers?) If available, please mention specific simulated cadences, and specific metrics, that support your answer.

(No response.)

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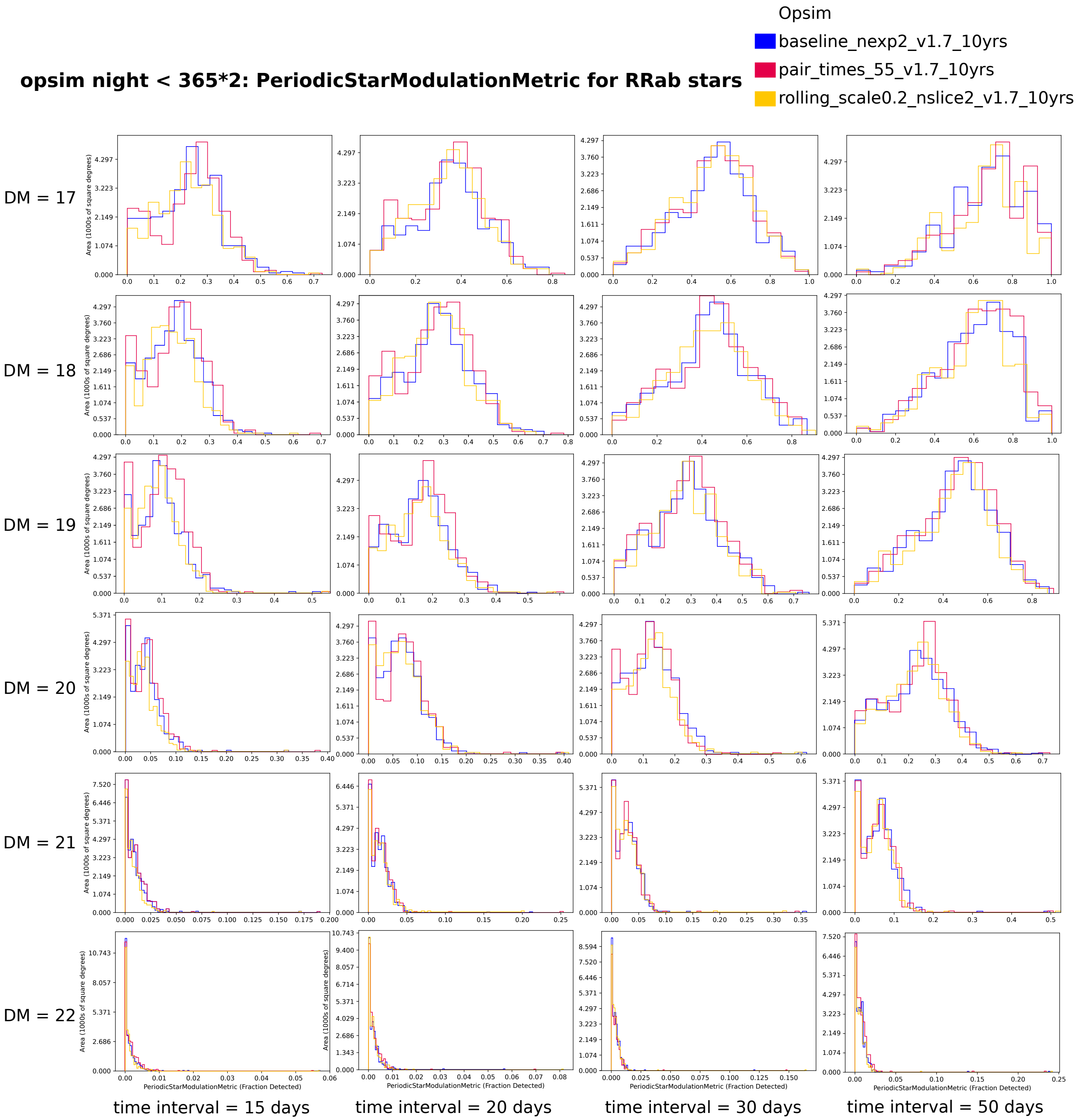

Figure 1. We plot the area (in 1000s of square degrees) for which a given fraction of RRab stars with a given distance modulus (17 to 22) from a light curve with a given time interval (15 to 55 days) can be identified. The metric was evaluated on simulated 2-year light curves for OpSim 1.7 databases `baseline_nexp2_v1.7_10yrs.db` (baseline), `rolling_scale0.2_nslice2_v1.7_10yrs.db` (rolling cadence) and `pair_times_55_v1.7_10yrs.db` (pair times cadence). A similar graphic for RRc stars can be found in our repository.