Young stellar objects and their variability with Rubin Observatory LSST

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1 Introduction

The Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST) will be the ideal instrument to allow us to investigate the variability of young stellar objects (YSOs) in star forming regions (SFRs) across all the very different time scales related to accretion, including eruptive events, in addition to different phenomena such as modulation due to rotation, extinction due to warp disks, or flares. These processes exhibit variations on different timescales from short-term (hours[1], days) to long-term (months and years, e.g. EXors and FUors objects undergoing eruptive accretion bursts). The short time scale events should be monitored with a properly populated light curve (LC) that samples all relevant time intervals. We can use Rubin LSST both to discover new accretors for classification and to characterize known objects. To this aim, we can obtain supporting ground-based data - e.g. synoptic spectroscopy. A follow-up program with different instruments, for spectroscopic investigation with FLAMES and SoXS or WEAVE and possibly 4MOST, where the PIs and many of the co-Is of this Cadence Note are strongly involved, will be planned. Since the proposed campaigns are only a week long, we could envision getting spectroscopy for the entire duration of the high-cadence observing (e.g. with SoXS and FLAMES) - which could be important to spectroscopically confirm accretion processes (e.g. from emission lines) and to constrain theoretical models. Accretion events are mainly evident in the bluest filters available in Rubin LSST, such as g, r, and i-band (u-band if possible[2]). We have identified as ideal a coverage of the LC with 140 points in 1 week for each filter: one point every 30 minutes in a 10 hour/night observation for 7 consecutive nights in each of the following filters: g, r, and i, to characterize short-term variability processes. Therefore, a combination of this project and the main survey with Rubin LSST will allow us to characterize all kind of variability in YSOs, from short-term to long-term.

2 Science Case

The requested sampling of 20 points each night, spaced by 30 minutes, for 7 consecutive days (140 points in total to be collected with Rubin LSST) is motivated by the fact that this sampling will allow us to reveal

[1]See also Bellm et al. Cadence Note
[2]We need new Moon for this filter, especially for faint sources

short-lived phenomena in YSOs (bursts, [Stauffer et al. 2014][3], or flares) with a probability of 50% (Fig. 1). The expected burst detection rate is strongly reduced if a lower number of points in the LC will be collected (Fig. 1). Of course, by reducing the number of points, we will also lose sensitivity to the shortest variable processes. In order to extract these statistics, we analyzed the light curves of YSOs with bursting variability behaviors (driven by intense and unstable accretion activity; e.g., Fig. 2), detected with K2 in NGC 6530 and with CoRoT in NGC 2264. By randomly generating an initial epoch, within each LC, for the simulated observing window with Rubin LSST, we iteratively extracted a 7-day segment from the satellite time series, and retained 10 hours of data every 24 hours within that segment to reproduce the night/day alternation that will be present in Rubin LSST ground-based observations. We then considered alternative samplings in our simulated datasets: one point every 30 minutes (the same cadence as K2), and lower cadences of one point every 45, 60, 90, 120, and 180 minutes. In each case, we define a burst detection when the selected points in the light curve cover at least one original bursting event (from bottom to peak), as well as the out-of-burst luminosity level for comparison. Using the K2 data of NGC 6530 and CoRoT data of NGC 2264, the probability of detection of the bursts are up to 50% using the 30 minutes cadence, 47% with 60 minutes, and 38% with the 120 minutes cadence. The unique capability of Rubin LSST will be complemented with archival LCs from, e.g., TESS, KELT, ASAS-SN, and other previous all-sky surveys from space and the ground that can be used for "precovery" ([Yao et al. 2019]), i.e. to check for historical variability to put the variations observed by Rubin Observatory into a larger context.

We propose to start this project focusing on Carina Nebula. The choice of Carina Nebula is based on the fact that it guarantees a large number of sources and it is well placed for observations from Chile with Rubin LSST (see the 2011 Special Issue of ApJ Supplements, Townsley et al., with 11,000 members identified, 100,000 extrapolated total population). We propose to then repeat the same observing strategy in different SFRs, as Orion Nebula Cluster, NGC 2264, NGC 6530, NGC 6611[4], to investigate the evolution of the processes producing the variability we want to study, and the effects of different ambient conditions. Early-time observations of Carina Nebula following the project here described will be important to explore the other SFRs after the analysis of the first results for variability in YSOs at different time-scales.

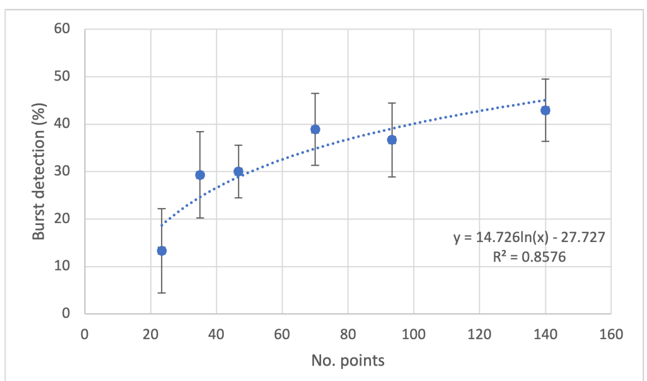

Figure 1: Probability of burst detection as a function of number of points in the LC. We stress that the points need to be distributed uniformly over 7 consecutive days and within each night, assuming 10 hours of observations per night.

3 Metric description

From Fig. 1, we define as Figure of Merit, FoM = 1 the proposed case where we collect 140 points in 7 consecutive days in each of g, r, and i filters (possibly also in u-band), with a cadence of 1 point every 30 minutes each night (10 hours long). Since no OpSim fitting these requirements[5] is available in the Rubin

[3] We acknowledge the support that John Stauffer (1952–2021) gave to this project since the preparation of the WP Bonito & Hartigan et al. 2018

[4] See also Street et al. Cadence Note and the plot https://github.com/LSST-TVSSC/software_tools/blob/master/footprint_maps/Bonito_regions_footprint_map.png

[5] An input list time-filters provided to P. Yoachim

LSST database, a new OpSim has been developed by P. Yoachim[6]. We have explored different OpSims by using two different metrics[7] to fit our scientific requirements. Here we discuss our results. Using the modified version of TransientAsciiMetric.ipynb, we obtain that: a) on a generic Wide Fast Deep (WFD) field with the OpSim baseline_nexp2_v1.7_10yrs.db, we collect ≈ 0 points in 7 consecutive days (see Fig. 2, left panel) to populate the LC of a hypothetical YSO at that location, exemplified in Fig. 2 by using as input the LC of a burster in NGC 2264 that we used in our simulations. Therefore, this OpSim corresponds to a bad scenario for our science case; b) on one of the currently selected Deep Drilling Fields, DDF, if we pretended Carina was at their position, we collect 40 points with the OpSim baseline_nexp2_v1.7_10yrs.db (see Fig. 2, right panel), but 100 points in 7 days using the OpSim ddf_heavy_nexp2_v1.6_10yrs.db. However, the points are not sampled every 30, 60, nor 120 minutes (see Fig. 3), but are rather clustered around very short time intervals and do not provide a uniform sampling of the 7-day window. Therefore also these cases correspond to bad scenarios to explore the variability in YSOs. Using the new OpSim carina_v1.7_10yrs.db and the "Carina metric", we can reproduce the requirements of [Bonito and Hartigan et al. 2018] (see Fig. 4 and Fig. 5). Therefore, this OpSim represents the only case that is good to investigate short-term variability in YSOs (e.g. bursters). An analogous OpSim with a reduced number of total points, i. e. corresponding to a cadence where each consecutive point is collected every 60 or 120 minutes, could represent an intermediate case, with a science loss of $\approx 25\%$ in our ability to identify short-term YSO variability, while longer cadences of 1 point every 180 minutes or less would cause a loss of $> 50\%$ for our science case (see Fig. 1).

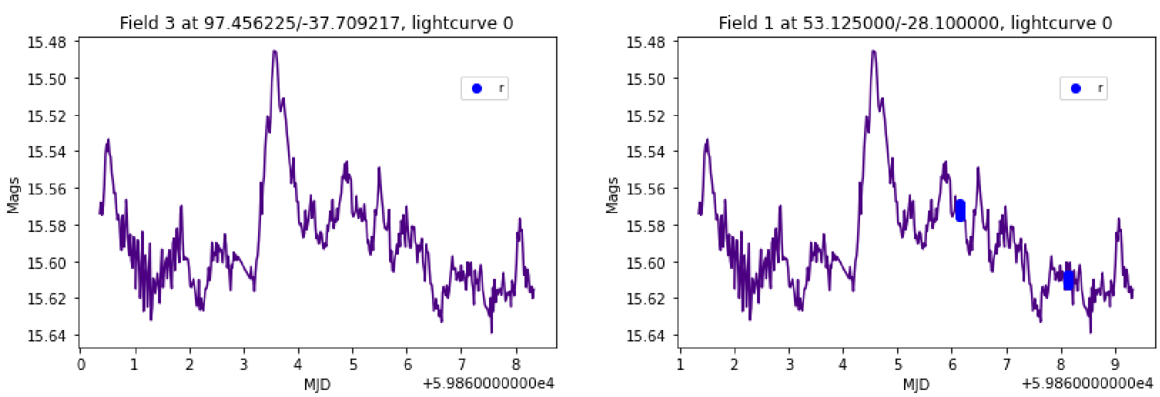

Figure 2: OpSim db = baseline_nexp2_v1.7_10yrs; a WFD field with zero points (left panel); a DDF with 40 points (right panel).

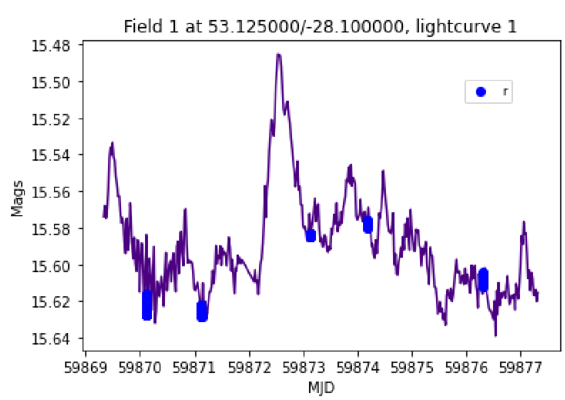

Figure 3: OpSim db = ddf_heavy_nexp2_v1.6_10yrs; a DDF with 100 points.

[6]https://lsst.ncsa.illinois.edu/sim-data/sims_featureScheduler_runs1.7/technical/carina/carina_v1.7_10yrs.db

[7]https://github.com/yoachim/21_Scratch/blob/main/carina_check/carina2.ipynb, that we will call here "Carina metric", as well as a modified version of TransientAsciiMetric.ipynb

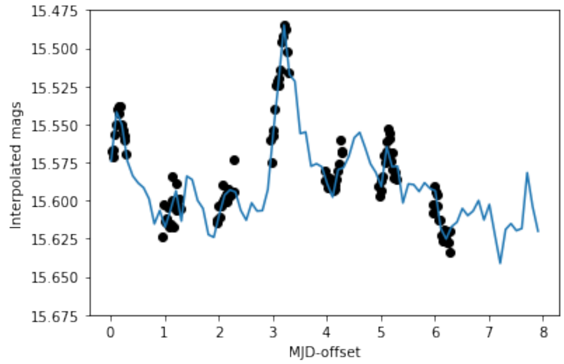

Figure 4: OpSim db = carina_v1.7_10yrs; the Carina Nebula pointing with the proper number of points covering the LC.

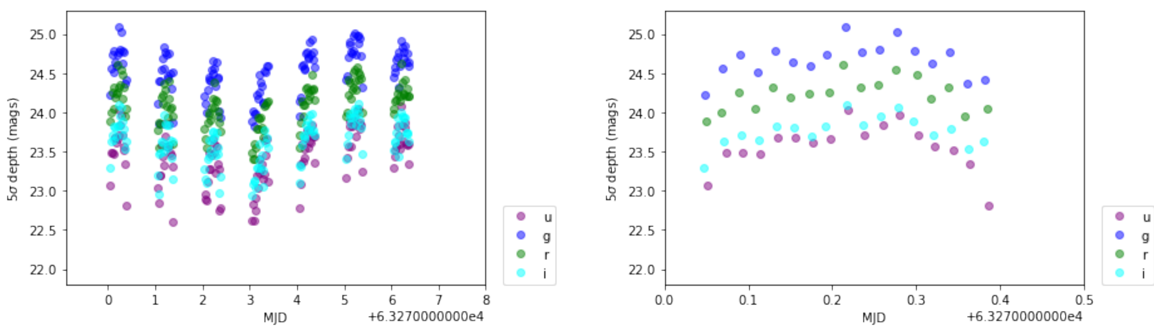

Figure 5: OpSim db = carina_v1.7_10yrs; more than 100 points per filter in one week (left panel), ≈ 20 points per filter in each night, corresponding to the required cadence of 30 minutes for 10 hours each night in each filter, ugri (right panel).

Additional plots and information can be found at the link: https://github.com/sbonito/Cadence-Note-YSO.

It is worth noting that the OpSim carina_v1.7_10yrs.db represents the best scenario for investigating the YSOs short-term variability only if we can obtain a complete set of 7 consecutive days. In fact, not all the weeks in this OpSim are complete: there are some gaps in some days: see Fig. 6.

We have checked that the science impact (in term of telescope time-consuming) of our project (e.g. one week every year devoted to investigation of YSOs variability with the requirements here described) is not very large for the whole survey, as the changes are not significant on all science metrics we have tested[8].

4 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.

Our science scales more strongly with the number of visits per pointing, once the proposed SFRs will be observed, starting with Carina Nebula. Therefore, it depends on where the additional area is added.

In particular, we need 140 points with a cadence of one point every 30 minutes each night (10 hours) in each of the (u), g, r, and i filter to properly reconstruct the LC to classify the short-term variability in YSOs (bursts; see Fig. 1). This is the case of the new developed OpSim carina_v1.7_10yrs.db, our best scenario

[8]The carina MAF outputs, carina_v1.7_10yrs, are online at http://astro-lsst-01.astro.washington.edu:8081/

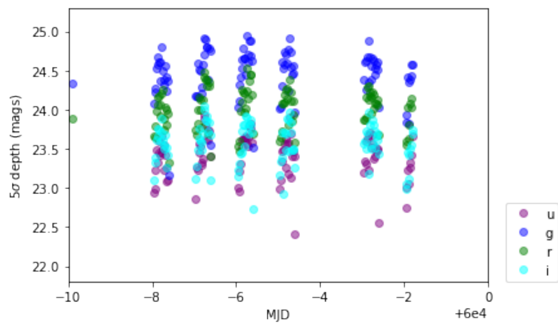

Figure 6: OpSim db = carina_v1.7_10yrs; 7 nights, but with a gap of one night

corresponding to FoM = 1. If the total number of points that we can collect is lower, e.g. with the cadence providing a point every $> 60 - 120$ minutes, we will not be able to investigate short-term variability.

It is worth noting that further optimisation of the proposed project is possible by selecting SFRs closer to main survey fields. In fact, our program can be efficiently coupled to the main survey in further investigations by selecting additional SFRs located closer to main survey fields so that visits to our fields and main survey fields can be alternated in a given filter (for instance g, r) to take best advantage of the continued filter change strategy proposed. Furthermore, synergy science is possible as e.g. fast microlensing events are another science that would benefit from observations on hours timescale, and it would be efficient to add LMC and SMC pointings intermixed with the Carina pointings.

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.

A fraction of the additional observing time can be used on selected SFRs or for the minisurvey Galactic Plane, GP, fundamental also for SFRs in general and variability in YSOs, both for short-term variability as here discussed and for long-term variability, as EXors-type variables. To investigate YSOs and their variability, we stress that the survey area of the WFD should be extended to include the Carina Nebula and the SFRs described in the WP [Bonito and Hartigan et al. 2018], as a following step of our analysis (i.e., starting the proposed exploration at high cadence as here described in Carina Nebula, and then repeating on different SFRs as e.g. Orion Nebula Cluster, NGC 2264, NGC 6530, NGC 6611). The coverage of the GP (see also the Cadence Notes Prisinzano & Bonito et al.; Street et al.) will be fundamental to explore the variability of YSOs in other SFRs with respect to Carina Nebula, using the same observing strategy here discussed (see also the WP [Bonito and Hartigan et al. 2018]). However, none of the available OpSims allow us to have the minimum number of points and proper sampling required to retrieve the proper shape of the LC from which to discriminate among the different processes at work and to classify the short-term variability (bursts), except the new OpSim carina_v1.7_10yrs.db. The OpSims baseline_nexp2_v1.7_10yrs.db and ddf_heavy_nexp2_v1.6_10yrs.db will not allow us to have enough points and a cadence of one point every 30 minutes as here discussed.

5 Exposure time per visit

Q3: Are there any science drivers that would strongly argue for, or against, the proposal to change the u band exposure from 2x15 sec to 1x50 sec? If available, please mention specific simulated cadences, and specific metrics, that support your answer.

The use of the u-band is important to explore accretion in YSOs. In classical T Tauri stars (CTTSs, accreting sources), blue band fluxes rise more strongly during accretion events, which we can distinguish from extinction events if red magnitudes are also available. Furthermore, the r-band data will be important as from the color magnitude-diagram (CMD) r vs. u-r, we can identify the weak-line T Tauri star (WTTS, non-accreting sources) members of the cluster, while a bluer spread characterizes the CTTS members, as the u-band excess is related to the accretion activity only present in CTTSs. Therefore, an important discrimination between WTTS and CTTS among the cluster members can be performed (see an example for the case of NGC 2264 in [Venuti et al. 2014], their Fig. 6). In addition, this allows us to obtain a direct measurement of the UV excess (and consequently of the accretion luminosity) of CTTSs with respect to the photospheric emission typical of the WTTSs. An exposure of 1x50 sec could be better in the u-band, as our sources are intrinsically fainter in this band and the effect of extinction is more pronounced there compared to redder filters.

6 Allocation of observing time per band

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.

Observations more towards the blue bands are fundamental for our science case, as the ugri filters are the ones we are requiring in this project. In fact, blue bands are probes for the accretion process that we want to investigate, as described above.

7 Time sampling and revisit offsets

Q5: Are there any science drivers that would strongly argue for, or against, obtaining 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.

This issue, as stated in Q5, does not exactly fit our case. Our science case requires several points each night in the same filter and in different filters, as detailed above.

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 SFRs in the Galactic Plane, by providing higher-cadence lightcurves for the cases that we have defined as long-term variability (e.g. EXors). For the short-term variability we propose to investigate, we need several points each night in the same filter and in different filters to discriminate different processes by investigating the morphology of the LCs for classication purposes.

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 strong requirements for dithering are needed, but it can be useful to reject spurious detections.

References

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