Young Stars and their Variability with LSST

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Abstract

Young stars are characterized by photometric variability due to diverse physical processes: mass accretion events from circumstellar disks, presence of warps in the inner disks, evolution of stellar angular momenta, starspot longevity and cycles, and flares. We aim at investigating in statistical samples in young stellar clusters the stellar variability due to accretion process, also in eruptive bursts (EXors); rotation; stellar activity; etc.. We propose to observe Carina with a cadence of 30 minutes every night for one consecutive week per year to sample the light curves in different bands to follow the short-term variability described and link this with the related physical processes. LSST will make a significant impact by providing large enough samples to allow us to relate these aspects of the young stars and their environments to stellar properties such as mass, age, binarity, and their location in a statistically significant manner.

1 White Paper Information

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1. **Science Category:** Exploring the transient optical sky

   Mapping the Milky Way

2. **Survey Type Category:** Deep Drilling field

3. **Observing Strategy Category:**

   - an integrated program with science that hinges on the combination of pointing and detailed observing strategy

2 Scientific Motivation

Young stellar objects (YSOs) are characterized by photometric variability due to diverse physical processes: mass accretion events from circumstellar disks, presence of warps in envelopes and disks, creation of new knots in stellar jets, stellar rotation, starspots, magnetic cycles, and flares. By exploiting stellar variability, we will study, in statistical samples in young stellar clusters, the properties of the physical processes involved. In particular, we aim at constraining open issues related to: the accretion process and its intrinsic variability (including eruptive bursts, as those of EXors-type variables), the evolution stellar rotation, the spatial distribution of stellar rotation in young clusters, stellar magnetic activity, and accretion and inner disk geometries.

LSST, by providing photometric monitoring of large stellar samples, will make a significant impact in our knowledge of the nature of young stars. Large samples are fundamental to understand how all these physical processes depend on stellar properties (such as mass, age, binarity), and/or on stellar location, and to understand the ongoing physical processes and their evolutionary stage. This will have a strong impact on the theoretical description of such complex objects. With the observation cadence we propose we aim to study spot induced rotational modulation, variability due to warps in disks, and, even as secondary priority, differential rotation. Knowing the rotation periods of thousands of young stars and the level and properties of their photometric variability within a given star forming region (SFR) will be a major contribution that LSST will provide to this field of research. The information derived from LSST photometric timeseries will allow us to learn how angular momentum is distributed among newborn stars, whether it changes with mass, multiplicity, and location in the cloud, and how it varies as the stars age. LSST will allow us to survey the outstanding collection of SFRs in the Southern hemisphere, including the closest low-mass SFRs (rho Oph, CrA, Cha I and Lupus), and the most famous intermediate-mass (Orion, Vela) and massive (Carina) SFRs. Monitoring mass accretion with a survey based on statistical samples of members of stellar clusters is desirable as accretion is a crucial process in early stellar evolution, regulating the star-disk interaction and influencing the dynamical evolution of both the central object and the protoplanetary disk. The investigation of large samples of young members of stellar clusters encompassing a variety of parameters is crucial to studying the evolution of the accretion on an individual vs. statistical basis. Photometric variability, on short- (hours), mid- (days, months), and long-term (years) timescales, is part of the definition of classical T Tauri stars (CTTSs; Joy 1945). Amplitude variability in CTTSs can be up to a few mag (Venuti et al. 2015; Stauffer et al. 2014). Buster-type objects identified in NGC 2264 (Stauffer et al. 2014) and TW Hya (Siwak et al. 2018) provide examples of variable accretion, as such short timescale variability is not produced by long-lived spots or flares. Different source of variability (e.g. stellar flares, accretion bursts, absorption due to warped disks, rotational modulation due to spot) can be easily discriminated among themselves because of their significantly different characteristics (see examples in NGC 2264, Stauffer et al. 2014, Flaccomio et al. 2018).

The accretion process in young stars is also investigated with detailed 3D magnetohydrodynamic (MHD) models of the infalling material: when we observe the accretion streams through line of sight the variability in the inverse P Cygni profiles can be accounted for (Kurosawa & Romanova 2013; see also the role of the local absorption for other wavelength emission in Bonito et al. 2014 and Revet et al. 2017, Science Advances). The investigation of the accretion mechanisms in YSOs can mainly be performed taking advantage of the analysis at short wavelengths, which provides a direct probe to the hot emission from the impact of accreting material onto the stellar surface at near free-fall velocities, which produces a shock several 10^3 K hotter than the stellar photosphere: the resulting UV excess luminosity is a proxy to the accretion luminosity and consequently of the mass accretion rates (see Gullbring et al. 1998 and Venuti et al. 2014 for a complete description). These variations are clearly visible and their amplitudes measurable in the blue bands (g filter). While accretion effects dominate in the blue filter data, they are still pronounced near $9000\AA$ (z-band) in the case of TW Hya (Siwak et al. 2018). With the proposed LSST observations, we can characterize different class of LCs (see Fig. 1): i) light curves dominated by accretion bursts (Stauffer et al. 2014); ii) light curves showing periodic or quasi-periodic flux dips (associated to rotating inner disk warp occulting the stellar emission, Bouvier et al. 2007a; Alencar et al. 2010). Analysis of available data from previous surveys as well as the development of diagnostic tools will be used to investigate the proposed questions. We plan to take advantage of data collected in existing surveys and previous programs (as many team members are involved in Gaia-ESO Survey, Chandra, etc.) to characterize the interesting fields and objects also using a multi-wavelength approach. We plan to obtain supporting ground-based data - e.g. synoptic spectroscopy. Since the proposed campaigns are only a week long, we plan to ask for spectroscopic data for the entire duration of the high-cadence observing - which could be important for detailed comparison to models, e.g. with FLAMES, which will allow us to cover the whole region of interest. A large accretion event is also a powerful way to select interesting systems for further observations with other instrumentations to look for evidence of a newly-created jet knot and will constitute the triggering alarm to observe the same objects with other instruments and in different bands (from X-rays to IR).

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 LSST (see the 2011 Special Issue of ApJ Supplements, Townsley et al., with 11,000 members identified, 100,000 extrapolated total population). The Carina Nebula hosts several very massive stars clustered in some of its SFRs. Thus, it is characterized by regions where disks evolution can be externally affected by photoevaporation and close encounters (e.g. Guarcello et al. 2016), and quieter regions where they can evolve unperturbed. We will be able to test the external feedback on disks evolution from variability-based diagnostics for the first time. Feigelson et al. 2011 also find many (thousands) are dispersed outside of compact clusters or clouds, so it is quite reasonable that there will be a vast population beyond the central 1 sq.deg. LSST with its unprecedented sensitivity, spatial coverage, and observing cadence will allow us for the first time to employ a statistical approach for the comprehension of the star formation process.

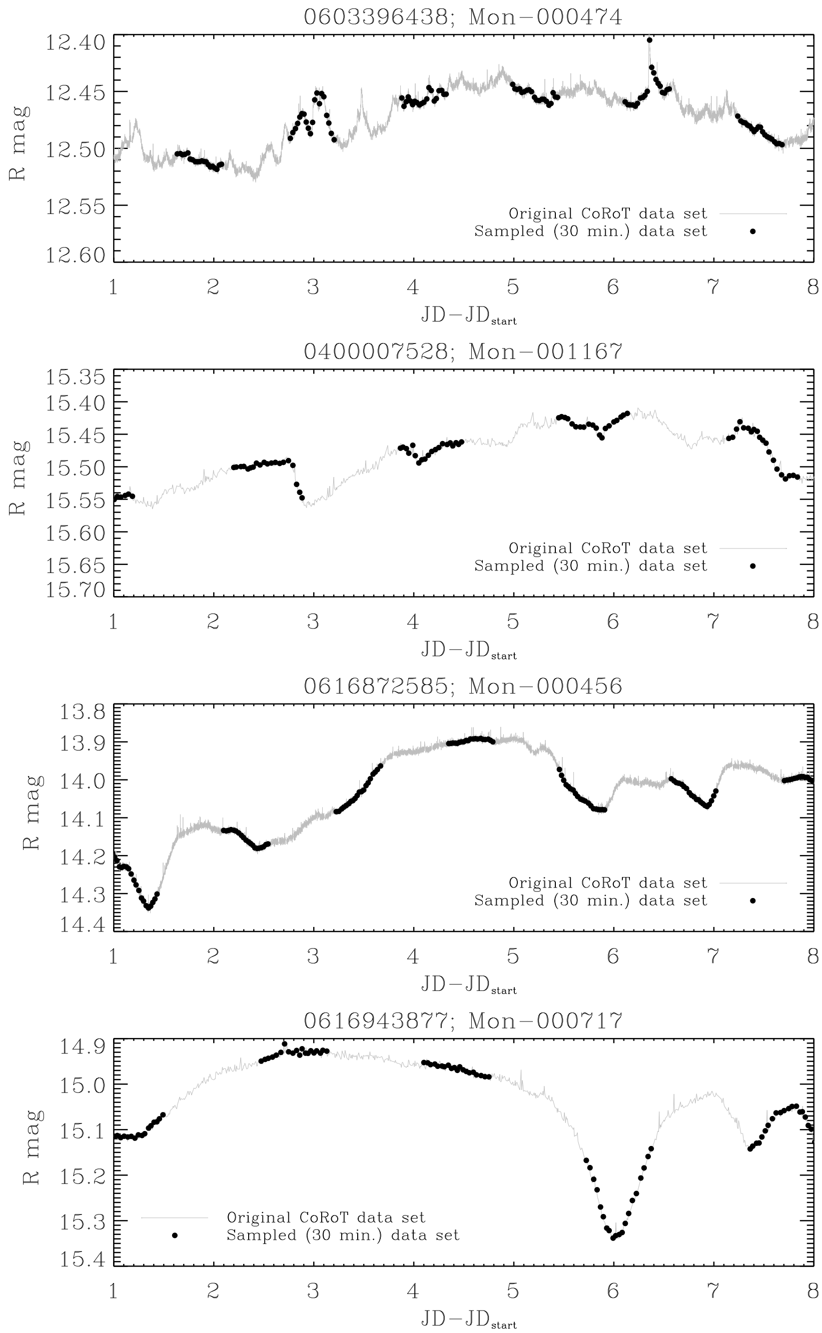

Figure 1: The light curves in the r-band of stars showing short-term variability due to accretion, flares, and dip due to warp disk, as observed with Corot (see also Stauffer et al. 2014) and with 10 hours of observations per night for 7 days with the 30 minutes cadence here requested. Accretion bursts as well as flares can be discriminated from the LC shape analysis (e.g. in upper panel). Therefore, the physical process responsible for the LC shape can be derived: stochastic accretion burst vs. periodic cold spot modulation vs. flare vs. dip possibly due to a warp circumstellar disk, well justifying the proposed cadence (30 min in the same filter). Even if the data would be noiser than Corot and with 2/3 missing, we still will be able to reconstruct the proper LC shapes.

3 Technical Description

3.1 High-level description

A dedicated campaign to observe star-forming regions at time intervals of an hour or less is required to capture the shorter-period systems. While a sparse coverage of one observation every few days, as in the main Wide-Fast-Deep (WFD) survey, is adequate for identifying sudden changes due to accretion events, a dense phase coverage (as proposed in this project), instead, will allow us to check the reliability of any periods recovered from sparse data in these objects, as well as to follow the short-term variations that characterize accreting systems. Any cadence will uncover FU Ori and EX Ori events in all filters. Nominal cadences that return to a star-forming region every 3-4 days will not suffice to derive accurate LC shapes from which we can deduce the physical process at work (accretion, occultation due to warp disk, rotational modulation of cold spots). These cadences, however, are adequate to detect major episodic accretion events like FU Ori and EX Ori on long term. However, a more focused annual campaign of about a week duration is necessary to recover the LC shapes to characterize the physical mechanisms producing specific LCs, as well as for period recovery and angular momentum studies of young stars. With the proposed selection of 3 filters (g, r, and i), our data will better be able to distiguish exact physical mechanisms (e.g. hot vs. cold spots). Therefore we ask for a rolling cadence program: occasional dense coverage of targeted regions is the only way to get quantitative information on short-term accretion, flare activity, and to recover rotation periods in strongly accreting stars. We plan to start with the Carina Nebula, which covers 1 square degree, during the first year of requested observations, and then we will follow up on different regions every year or with possible return to the same regions. For CTTS, which have a complex irregular light curves, dense coverage also removes degeneracies for periodic variables that have periods less than a day.

The embedded and CTTSs also undergo significant and rapid color changes due to both accretion processes and extinction variations, so it is important to include multiple filters in any dense coverage campaign. These goals can be accomplished by having a week of observations every year where one selected field is observed once every 30 minutes in g, r, and i bands. A young star with a 2-day period sampled every 30 minutes provides a data point every 0.01 in phase. For the best-case scenario, observing for 7 nights and 10 hours per night would yield 140 photometric points in each filter.

Depending on the period aliasing, this coverage should populate the phases well enough to identify most of the large starspots on the stellar photospheres. At the beginning of LSST operations we argue that a targeted test field (Carina Nebula) should be observed in this manner to illustrate what can be done with LSST in this mode. Combining a densely-packed short-interval dataset with a sparse but long baseline study maximizes the scientific return for both methods, and allows LSST to address all of the accretion and rotational variability associated with young stars. Time-intensive (one week/year) campaign on a few selected regions will greatly improve our ability to separate periodic variables from aperiodic ones.

3.2 Footprint – pointings, regions and/or constraints

The first target requested for the first year of observations in this program is the Carina Nebula. The pointing should be centered on Eta Carinae (RA, Dec = 10 45 03.5362075818 -59 41 04.053436648, ICRS coord., ep=J2000). Other SFRs can be considered in the next years observations, after the data analysis of first year observations is obtained in the context of this program for Carina Nebula. Examples are: Orion Nebular Cluster, NGC 2264, NGC 6530, NGC 6611.

Galactic star formation regions are largely found at low Galactic latitudes or within the Gould Belt structure. As such study of young stars with LSST is closely tied to other science goals concerning the Milky Way Disk and is subject to the concerns of both crowded field photometry and the observing cadence along the Milky Way. However, DECam observations at the CTIO 4-m that reached depths similar to those proposed for LSST show negligible crowding in the optical, and $< 5\%$ crowding at z in Carina. In this case, extinction in the molecular clouds helps by significantly lowering the frequency of background contamination. Owing to extinction in the dark clouds, source confusion will generally not be an issue (as evidenced by typical deep optical images of such regions). Most young stars congregate into clusters in specific regions, though there is an older population that is more distributed. The vast majority are within about 25 degrees of the galactic plane.

The requirement of taking advantage of studying stars in clusters is well justified as we can investigate variability across a large statistical sample of coeval pre-main sequence (PMS) stars, all similarly characterized. Bursts in LCs are real and not an artifact, not present in field stars (Satuffer et al. 2014), so it is useful to have a large FoV as the LSST one for the observations of a large sample of both members and field stars.

3.3 Image quality

Better seeing helps with unresolved binaries and for regions where contamination comes into play, for example, in the plane but away from dark clouds.

3.4 Individual image depth and/or sky brightness

Some of the fainter objects will be affected if the Moon is very bright and close. However generally these constraints are probably in a typical category and will not affect the design of the survey. Considering DECam 60-sec r-band images, it is possible to get very good photometry down through r=20, and it starts to fall apart by r=21, for data collected with a 100% full Moon. According to the CTIO website, that amounts to about 18 mag/sq-arcsec, which adds to the noise.

3.5 Co-added image depth and/or total number of visits

Deep coadded frames are a secondary priority.

3.6 Number of visits within a night

As observed in classical T Tauri stars (as TW Hya, Siwak et al. 2018) variability ranging from 30 min to several hours is expected, due to the accretion process that we aim at investigating. A time sampling on timescales short enough to trace the short-term variations (<hours; flare, burst) and extending over timescales relevant to various processes is needed to achieve a detailed physical description of the mechanisms at work at the stellar surface and in the star-disk interface (Venuti et al. 2015). In general, a small number of epochs and irregular cadence does not allow one to discriminate the physical nature of the variability (see discussion on this issue in Stauffer et al. 2014). We therefore require observations once every 30 minutes, 10 hours per night, for 7 nights. This would yield 20 photometric points in each filter (each night), in order to populate the phases well enough to identify most of the large starspots on the stellar photospheres and track other expected sources of variability. Data taken in the same band per night means better sampling for period determination.

In the case of TW Hya (Siwak et al. 2018) 0.59 flare/d or 0.94 (flare or accretion burst)/d have been derived, with accretion burst period up to 30 min. Therefore, we expect to observe several peaks in the LCs collected each night with the proposed cadence. As an example, in BP Tau, calculation from models allowed the derivation of cooling times after impacts of accretion material of 30 min - several hours, in accord with observations of the shortest bursts in BP Tau (0.6 h; se discussion in Siwak et al. 2018).

3.7 Distribution of visits over time

Variability due to stellar activity, to accretion process including eruptive bursts (EXors), to rotation, etc., will benefit from higher cadence observations exploring clusters with different ages, metallicity, and location. The Galactic Plane should be investigated with a cadence higher with respect to the Main Survey to follow the variability of stars. Therefore, we ask for a week long run of 10 hours per night with observations every 30 min each year. Higher cadence observations are needed in order to clearly characterize the physical mechanisms (Stauffer et al. 2014). As an example, Venuti et al. 2014 explored the mid-term variability in NGC 2264 and measured the UV excess (and correspondingly computed the mass accretion rate) from each observing epoch during the CFHT r-band (and u-band) monitoring, obtaining ≈ 17 points distributed over the 2-week long survey to probe variability. Stauffer et al. 2014 found a burst frequency of 0.2 peak per day and typical total duration of isolated accretion burst of 1 d. Therefore we expect to be able to observe 1 peak in about 5 days, in good agreement with our proposal to observe with LSST with a rolling cadence of 1 week every 30 min in g, r, and i filters: the higher cadence requested would allow the detection of many shorter duration (hours) events.

If for weather patterns part of the night is lost due to e.g. clouds, the science is still achievable (there is no need to the whole sequence to be redone).

Figure of Merit (FoM): In the proposed program, we expect to collect 140 points in each filter (g, r, and i) in 1 week. The Wide Fast Deep (WFD) main survey will allow to collect 80, 180, and 180 visits in g, r, and i filters respectively in ten years of LSST Survey.

Therefore in the WFD scenario, we would collect 0.15, 0.35, and 0.35 observations per week in g, r, and i filter respectively instead (while 140 in the proposed rolling cadence), losing a big fraction of points (the ratio being 0.15/140 or 0.35/140, i.e. 0.00107143, 0.00250000), but, more important, completely losing the possibility to follow the short term variability discussed above and to consequently discriminate the physical mechanism at play.

Number of visits on the Galactic Plane, in 10 years (p.55 SB, sect.3.1) are lower: < 30 in all filters (< 1 every four months), a very infrequent monitoring.

3.8 Filter choice

We request a rotation of g, r, and i filters every 30 minutes for 10 hours each night for 1 week each year (possibly changing the pointing every year, but starting with Carina Nebula the first year). In CTTSs, 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 (on long-term variability with the WFD main survey), we can easily identify the WTTS members of the cluster (the cluster locus coicides with WTTSs), 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, 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 proper of the WTTSs. The r-filter should suffice for most objects, though the most heavily-reddened sources would benefit from observations in the i-band. CTTSs show higher levels of variability, both in the optical (r band) and, more markedly in the blue bands (u and g), with typical photometric amplitudes about three times those measured for WTTSs (see Venuti et al. 2015 for the u-band in particular; see Siwak et al. 2018 for the g band). The LCs which are burst dominated, and therefore related to accretion process, have been found to be $55 - 80\%$ of the YSO with the strongest UV excesses in NGC 2264 (Stauffer et al. 2014). Flares also occur in WTTS as a consequence of high chromospheric activity. Flaring in WTTS can also be monitored, though the rapid decline of chromospheric flares requires a rapid cadence to capture correctly. The blue band allows us to follow mass accretion variability, while r (for most objects) will be dominated by photospheric flux. More colors are always useful, but having a photospheric color index plus one accretion measure are the science drivers for filter choices. For long-term variability also with the g-band, the color-color diagram (CCD) u-g vs. g-r allows us to derive another very interesting locus to identify accretors: the main distribution (cluster members in general and WTTSs) is well distiguished with respect to the u-band excess (the dispersion below), again characterizing the CTTS components with respect to the non-accreting (WTTS) components (see Venuti et al. 2014, Fig. 5). Furthermore, for the short-term variability investigated in this proposal, adding to the r-band also the g-band, we would obtain more constraints on the variability in different colours, crucial to discriminate different drivers of the variability itself in YSOs: hot spots vs. cold spots and circumstellar extinction. It is worth noting that (on long term) CCD u-g vs. g-r can also help for a re-classification of previously considered non-accreting members. In fact, the accretion process is intrinsically variable and during previous surveys low accretors could be misinterpreted as a non-accretor members. The position in the CCD u-g vs. g-r below the WTTS locus can be used as a strong test of variability and therefore allows us to classify those stars as CTTS. g, r, and i filters together could be important for the diagnostic of CTTS vs. WTTS in young clusters as CTTSs could appear blueward with respect to the main locus of the WTTSs (see also Venuti et al. 2014, Fig. 4), due to variability common in CTTSs with respect to the non-accreting counterparts. These results can also be confirmed taking advantage of spectroscopic data collected with FLAMES (also in the context of the GES collaboration, where the PI and many of the co-Is of this WP are actively involved) of the Halpha emission line (see also Bonito et al. 2013 and Bonito et al. in preparation for the CTTS/WTTS characterization and nebular contribution to the stellar Halpha emission in NGC 6611 and NGC 2264). In a g vs g - i CMD, we can compare the location of CTTSs with accretion burst, dips in the LCs, and WTTSs (see the example of NGC 2264 members in Stauffer et al. 2014, Fig. 9). The three different groups of stars appear coeval in general, with a smaller dispersion for the non-accreting component (see also Lamm et al. 2004). Stars with LCs dominated by accretion bursts have a location on the g vs g-i CMD affected by the hot spots formed due to accretion (Stauffer et al. 2014).

3.9 Exposure constraints

A rotation of 30 seconds exposuree in g, r, and i filters every 30 minutes for 10 hours per night for 7 consecutive days each year

3.10 Other constraints

None

3.11 Estimated time requirement

We request a week of observations every year once every 30 minutes in g, r, and i, bands. Observing for 7 consecutive nights and 10 hours per night would yield 140 photometric points in each filter. In more details: 10 hours (once every 30 minutes for 7 nights), 34 seconds per visit (taking into account shutter and readout)

1. g-band: 120 sec, for slew and setting; 30 sec exposure; 2 sec shutter; 2 sec readout

2. r-band: 120 sec, to change the filter; 30 sec exposure; 2 sec shutter; 2 sec readout

3. i-band: 120 sec, to change the filter; 30 sec exposure; 2 sec readout

Properties	Importance
Image quality	2
Sky brightness	2
Individual image depth	2
Co-added image depth	2
Number of exposures in a visit	2
Number of visits (in a night)	1
Total number of visits	1
Time between visits (in a night)	1
Time between visits (between nights)	1
Long-term gaps between visits	3
Other (please add other constraints as needed)	3

Table 1: **Constraint Rankings:** Summary of the relative importance of various survey strategy constraints. Please rank the importance of each of these considerations, from 1=very important, 2=somewhat important, 3=not important. If a given constraint depends on other parameters in the table, but these other parameters are not important in themselves, please only mark the final constraint as important. For example, individual image depth depends on image quality, sky brightness, and number of exposures in a visit; if your science depends on the individual image depth but not directly on the other parameters, individual image depth would be '1' and the other parameters could be marked as '3', giving us the most flexibility when determining the composition of a visit, for example.

3.12 Technical trades

This program is a rolling cadence of observations that should be performed in g, r, and i filters every 30 minutes each night (10 hours) for 7 consecutive days each year, to properly reconstruct the LC shapes to discriminate among different possible physical mechanisms at work in young stars.

4 Performance Evaluation

To quantify YSO studies with LSST, we consider V927 Tau, a rather faint, moderately-reddened 0.2 $M_{\odot}$ young star in the Taurus cloud as a target goal. Scaling the SDSS colors of V927 Tau, a typical low-mass T Tauri star, to Carina gives u=24.1, g=21.6, r=20.2, i=18.9 and z=17.9 mag. These previous results well justifies our choice of filters (i, r, and g) and allow us to say with confidence that we will get good r and i LCs of Carina's low mass T Tauri stars with LSST. We were able to get to r=20.2 with good precision with a 100% full Moon. Note that 30-sigma limits for each 4-minute dither sequence (good lightcurves) are u=21.6, g=22.5, r=22.3, i=22.0, and z=21.3. For reference, a typical young star in the Carina X-ray catalog has an i-magnitude of 18. Objects that suffer larger extinctions along the line of sight will be easiest to observe in the red. The universal cadence option of 2×15 sec exposures will yield sigma = 0.02 mag for r=21.8, a magnitude fainter than V 927 Tau would be in Carina. This photometric uncertainty suffices to recover a typical period from such an object. LSST will determine periods to near the hydrogen burning limit with nominal r-band measurements for a region like Carina.

5 Special Data Processing

6 References

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