Young Stars and their Variability with LSST

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Abstract

Young stars exhibit short-term photometric variability caused by mass accretion events from circumstellar disks, the presence of dusty warps within the inner disks, starspots that rotate across the stellar surfaces, and flares. Long-term variability also occurs owing to starspot longevity and cycles, and from changes in stellar angular momenta and activity as the stars age. We propose to observe the Carina star-forming region in different bands with a cadence of 30 minutes every night for one week per year to clarify the nature of both the short-term and long-term variability of the thousands of young stars in this region. By obtaining well-sampled multicolor lightcurves of this dense young cluster, LSST would acquire the first statistically significant data on how these objects vary on both short and long timescales. This information will allow us to relate the observed variability to stellar properties such as mass, age, binarity, and to environmental properties such as location within or exterior to the H II region, and to the presence or absence of a circumstellar disk.

1 White Paper Information

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with the support of the LSST Transient and Variable Stars Collaboration
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 caused by several distinct physical processes: mass accretion events from circumstellar disks, presence of warps in envelopes and disks, the creation of new knots in stellar jets, stellar rotation, starspots, magnetic cycles, and flares. We can study all these phenomena if we acquire both short-term and long-term lightcurves of a statistically significant sample of YSOs. This white paper outlines a strategy for maximizing the scientific contribution of LSST to this field of research.

As described below, measuring reliable periods for young stars requires a block of time where a star-forming region is observed regularly throughout the night for at least a week, and such observations are also ideal for studying flares, accretion pulses and disk warps. The nominal LSST universal cadence complements our proposed observations by quantifying long-term secular variability. Our proposed plan will address open questions related to accretion processes, intrinsic variability (including eruptive bursts, such as those of EXors-type variables), the evolution stellar rotation, the spatial distribution of stellar rotation in young clusters, stellar magnetic activity, and inner disk geometries.

LSST will make a significant impact on our knowledge of young stars by monitoring the brightnesses and colors of a large sample of these objects. Large samples are needed to quantify how the various physical processes listed above depend upon stellar properties (such as mass, age, binarity), environmental conditions (stellar location, presence of a circumstellar disks) and the evolutionary stages of the stars. This information will have a strong impact on the theoretical description of these complex objects. 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 unique contribution that LSST will provide to this field of research. The information derived from LSST photometric time series data 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 an 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 large samples of young stars is particularly desirable, as accretion is a crucial process in early stellar evolution. Accretion regulates the star-disk interaction and influences how the central object and the protoplanetary disk evolve.

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 sources of variability (e.g. stellar flares, accretion bursts, absorption due to warped disks, rotational modulation due to spots) can be easily discriminated among themselves from their significantly differing observational
characteristics (see examples in NGC 2264, Stauffer et al. 2014, Flaccomio et al. 2018).

Accretion mechanisms in YSOs are easiest to study at short wavelengths because the infalling material is heated to several $10^3$ K above the photospheric temperature as it impacts the stellar surface at near free-fall velocities. The resulting UV excess luminosity from the accretion shock is proportional to the total accretion luminosity and provides a measure of the mass accretion rates (see Gullbring et al. 1998 and Venuti et al. 2014 for a complete description). Variations in the accretion rate are clearly visible as amplitude changes in the blue bands (g filter), but can still be important even in the z-band for some objects (e.g. TW Hya; Siwak et al. 2018). Accretion process in young stars have also been investigated with detailed 3D magnetohydrodynamic (MHD) models of the infalling material, where such models account for the observed variability in the inverse P-Cygni line profiles as we view accretion streams along the line of sight to the star (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).

The proposed LSST observations will characterize different class of LCs (see Fig. 1), including light curves dominated by accretion bursts (Stauffer et al. 2014), and 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). We plan to take advantage of data collected in existing surveys and with 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. Because the proposed campaigns are only a week long, we plan to ask for spectroscopic data for the entire duration of the high-cadence observing. Contemporaneous spectroscopy, e.g. with FLAMES, will be important for detailed comparison with models for individual sources. A large accretion event is also a powerful way to select interesting systems for further observations with other instruments. For example, after an accretion event one could look for evidence of a newly-created jet knot. We will use accretion events to trigger an alarm to observe the same objects with other instruments and in different bands (from X-rays to IR).

The plan is to target one major star-forming region every year. Retargeting the same region in a subsequent year has the potential to uncover period changes that may arise from stellar differential rotation, and amplitude variations indicative of stellar cycles. Our initial choice of Carina Nebula is well-placed for observations from Chile with LSST, and guarantees a large number of sources (11,000 members identified; Townsley et al. 2011). Carina hosts several very massive stars clustered in some of its SFRs. Thus, it contains regions where disks are 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 thousands of X-ray sources 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 to employ a statistical approach for the first time to the comprehension of star formation processes.
Figure 1: The light curves in the r-band of young stars showing short-term non-periodic variability due to accretion, flares, and dips due to a warped disk, as observed with Corot (see also Stauffer et al. 2014). Bold-faced points mark periods of 10 hours 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). Even with uncertainties per point of \( \sim 0.02 \) mag and with 2/3 missing, we still will be able to reconstruct the proper LC shapes with the proposed 30 min cadence in each filter.
3 Technical Description

3.1 High-level description

While sparse coverage of one observation every few days like the Wide-Fast-Deep (WFD) survey is adequate for identifying sudden changes caused by large accretion events such as FU Ori and EX Ori outbursts, a dedicated campaign to observe star-forming regions at more frequent time intervals is required to capture the rapidly-rotating periodic stars, which have periods less than about a day. Denser phase coverage is also needed to follow short-term variations that characterize accreting and flaring systems. Embedded and accreting young stars also undergo significant and rapid color changes owing to both accretion processes and extinction variations, so it is important to include multiple filters in any dense coverage campaign. The 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 the above manner to illustrate what can be done with LSST in this mode. If successful, in subsequent years we will either choose a different region or possibly return to the same regions to monitor slow changes in periods or amplitudes that may arise from differential rotation or starspot cycles. 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.

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 10:45:03.5 3, Dec -59:41:04.1, ICRS coord., ep=J2000). Other SFRs can be considered in the future once the data analysis of first year observations is obtained in the context of this program. Examples of other SFRs visible from Chile include Orion Nebular Cluster, NGC 2264, NGC 6530, and NGC 6611.

Galactic star formation regions are largely found at low Galactic latitudes or within the Gould Belt. 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. By observing young clusters we take advantage of the ability to image a large number of coeval pre-main-sequence stars simultaneously. Field stars will be useful as controls to ensure than any bursts in the LCs of young stars are real (e.g. Stauffer et al. 2014).

### 3.3 Image quality

Better seeing helps to resolve close binaries, and is also important 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 secondary and do 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 become too noisy for good light curves once r=21 for data collected on Carina with a 100% full Moon. According to the CTIO website, the sky brightness is about 18 mag/sq-arcsec for a full Moon.

### 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

Accretion variability in classical T Tauri stars typically ranges from 30 min to several hours or longer (e.g. TW Hya, Siwak et al. 2018). Sampling on timescales short enough to trace the short-term variations (<hours; flare, burst) but 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 request observations once every 30 minutes, 10 hours per night, for 7 nights. This would yield 20 photometric points in each filter (each night), and will populate the phases well enough to identify most of the large starspots on the stellar photospheres and track other expected sources of variability. Data in each band (changing every 30 minutes g, r, and i filters) gives its own lightcurve, making it possible to follow how the colors vary with phase.

Siwak et al. 2018 derived a rate of 0.59 flare/day or 0.94 (flare or accretion burst)/day for TW Hya, with accretion bursts lasting up to 30 min. Therefore, we expect to observe
several peaks in the LCs collected each night with the proposed cadence. Models suggest accretion cooling timescales of 30 min to several hours in accordance with observations of the shortest bursts in BP Tau (0.6 h; see discussion in Siwak et al. 2018).

3.7 Distribution of visits over time

In this white paper we ask for an annual week-long run of 10 hours per night of a targeted region, with observations taken every 30 min to complement the universal cadence of one observation every few days. Variability due to stellar activity, accretion process including eruptive bursts (EXors), rotation, etc., will all benefit from higher cadence observations exploring clusters with different ages, metallicity, and location.

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 part of a night is lost due to poor weather, the science is still achievable (there is no need to the whole sequence to be redone). However, if several days are lost then a typical phase coverage will become sparse, so operations staff should use their best-efforts to schedule the observations during a week of continuously usable weather.

**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 collect 80, 180, and 180 visits in g, r, and i filters respectively in ten years of LSST Survey. In the WFD scenario, we would collect 0.15, 0.35, and 0.35 observations per week in g, r, and i filter respectively as opposed to 140 per week in the proposed rolling cadence. Recovering periods from WFD data will be impossible if the periods vary even slightly over a 10-year timespan. For example, a young star with a rotation period of 2 days will experience 1825 rotations in 10 years. If the period slows by just one minute over the 10 years time interval, the lightcurve will shift by 0.63 in phase, making it impossible to properly phase such sparse data. The planned number of visits in the Galactic Plane in 10 years (p.55 SB, sect.3.1) are especially low, < 30 in all filters (< 1 every four months), and completely unsuited for period studies.
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). Typical T Tauri stars will be too faint to observe at u using a rapid cadence with LSST, but the g-band is blue enough to use as an accretion diagnostic. In CTTSs, blue band fluxes rise more strongly during accretion events, so we can distinguish accretion from extinction events if red magnitudes are also available. Furthermore, the r-band data will be important as it allows us to construct a color magnitude-diagram r vs. g-r. We should be able to identify the WTTS members of the cluster, while a bluer spread characterizes the CTTS members, as the blue 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.

CTTSs show higher levels of variability, both in the optical (r band) and, more markedly in the blue bands such as 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 (r-i) plus one accretion measure (g-r) are the science drivers for filter choices. Variability in different colours helps to discriminate between hot spots, cold spots, and circumstellar extinction. A color-color diagram also helps to correct erroneously classified 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.

Classifications based on color can be confirmed spectroscopically with, for example, FLAMES observations of the Hα emission line (see also Bonito et al. 2013 and Bonito et al. in preparation). In the g vs g-i diagram, 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 diagram affected by hot spots formed by accretion (Stauffer et al. 2014).

3.9 Exposure constraints

A rotation of 30 seconds exposure 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. The total overhead is 34 seconds per visit as shown below. During the week that the campaign is active, it will use approximately 25% of the available observing time on those nights.

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 numbers motivate 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. 60-second exposures with DecCAM on the CTIO 4-m 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. The universal cadence option of $2 \times 15$ 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 exposure times for a region like Carina.

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