

Extragalactic Exoplanets – Higher Cadence Observations of SMC

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Abstract

We propose to increase LSST cadence for the Small Magellanic Cloud which will enable finding dozens of microlensing events annually and potentially, a few planetary events over the course of the survey. These would be the first extragalactic exoplanets ever discovered and will give us a unique constraint on the planet formation and evolution under different environments. We discuss what changes in the LSST observing strategy are required. Presented analysis takes into account an extensive photometric follow-up program.

1 White Paper Information

Please contact Radek Poleski, poleski.1@osu.edu, with any questions about this white paper.

1. **Science Category:** Exploring the Changing Sky
2. **Survey Type Category:** mini survey
3. **Observing Strategy Category:** an integrated program with science that hinges on the combination of pointing and detailed observing strategy (e.g., search for variable stars in the LMC/SMC).

2 Scientific Motivation

The deep understanding of planet formation and evolution requires studying planets in a wide range of environments. Currently known exoplanets are situated in the Milky Way and most of them are found close to the Sun because of higher sensitivity of transit and radial velocity techniques for brighter (hence nearby) host stars. Discovering extragalactic exoplanets is even more challenging than finding the Milky Way planets because of larger distances. High cadence observations of the Small Magellanic Cloud (SMC) by LSST will allow finding extragalactic exoplanets using gravitational microlensing technique.

Microlensing is sensitive to the lens mass, not light, hence, allows one to find very faint objects. Microlensing searches of exoplanets in M31 have not yet found planets, mainly due too small number of events (Ingrosso et al. 2009; Calchi Novati et al. 2014; Lee et al. 2015). The other possibility of finding extragalactic exoplanets with LSST — transit method applied to LMC — requires a dedicated Deep Drilling field (which is larger effort than proposed here) and candidate transit will be very difficult to confirm using even the next generation 30-m telescopes (Lund et al. 2015; Jacklin et al. 2015). In Mróz & Poleski (2018) we proposed to observe SMC with higher cadence, so that microlensing events can be found early and detection of planetary signatures in these events could be done using LSST data (if cadence is high enough) or using photometric follow-up observations from smaller telescopes. SMC is elongated along the line-of-sight and the microlensing events observed toward SMC are almost exclusively self-lensing, i.e., both the lens and the source are in SMC (Sahu & Sahu 1998; Wyrzykowski et al. 2011).

There are thousands of microlensing events discovered so far toward the Galactic bulge. Among these events, about 70 planetary events have already been published and more are being analyzed. The planetary companion to the microlensing host star shows its presence via short-lasting anomaly (Mao & Paczyński 1991; Gould & Loeb 1992) ontop of a point-source point-lens event (Paczynski 1986). The length of the anomaly is on the order of Einstein timescale of the host event multiplied by a square root of the mass ratio. Galactic bulge microlensing events have typical Einstein timescales of ≈ 20 days, hence, giant planets produce signals that last on the order of 1 day. Current Galactic bulge microlensing surveys (mainly KMT, OGLE-IV, and MOA-II, but also Wise and UKIRT) have cadence of up to 15-20 minutes which allows robust detection of gas- and ice-giant exoplanets using survey data only (e.g., Yee et al. 2012; Poleski et al. 2014; Shvartzvald et al. 2016). The alternative approach is to follow-up events found by surveys with a network of follow-up telescopes which can have small field-of-view cameras and, in many cases, smaller apertures. Follow-up observations are particularly useful for high-magnification events (peak magnification $\gtrsim 100$), which both have higher planet detection efficiency and can be recognized in advance (Griest & Safizadeh 1998; Gould et al. 2010). Median Einstein timescale of SMC events is ≈ 3 times longer than that of Galactic bulge events which leads to a longer timescales of anomalies. One-hour cadence in the SMC should be enough to efficiently find high mass-ratio planets.

The LSST telescope and camera have unique capability to study microlensing events toward SMC. The photometry from the on-going microlensing surveys is not deep enough

to allow finding large enough number of SMC events. LSST field of view is large enough to cover almost the whole region of interest in just a single pointing.

It is possible that planet frequency in the SMC is lower than in the Solar neighborhood. The correlation between stellar metallicity and planet frequency is well known (Fischer & Valenti 2005; Wang & Fischer 2015), but without performing proposed experiment we cannot be sure if it applies to smaller-mass hosts and wider orbit planets, which are probed by microlensing. Below we present expected yield that assumes fiducial planet frequency rate and request the experiment with yield of a few planets so that, scientifically interesting upper limits on the planet frequency can be derived if no planet is detected.

3 Technical Description

3.1 High-level description

Here we present technical description of a program where LSST sampling is enough to discover microlensing events and most of planet sensitivity comes from the follow-up observations. If most of planet sensitivity comes from the LSST observations, then cadence would need to be improved to 1 hour.

We propose for on the order of 2000 epochs to be taken in a single field in the SMC. The sampling should be uniform in time and only r , g , and i filters give the highest yield.

3.2 Footprint – pointings, regions and/or constraints

The large field of view of LSST allows covering almost the entire sky-region of interest in a single pointing. It would be best to center the pointing at R.A. = $0^{\text{h}}58^{\text{m}}$, Dec. = $-73^{\circ}00'$.

3.3 Image quality

Due to high crowding of the field, we request observations with seeing < 2 arcsec.

3.4 Individual image depth and/or sky brightness

We request r and g band image depths of $\lesssim 23.5$ mag and i band depth of $\lesssim 23.0$ mag. The depths may be relaxed at the begin and end of SMC observing season in order to extend time interval each year.

SMC is located close to South ecliptic pole, hence can be observed independent of Moon phase.

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

High detection efficiency for microlensing events requires uniform sampling and cadence on the order of 1 day. This translates to on the order of 2000 epochs after accounting for visibility and weather constraints.

There is no direct constraint on the co-added image depth.

3.6 Number of visits within a night

The optimal strategy is to take one or two epochs per night. If there are multiple visits during one night, then they should be separated by at least 1 hour.

3.7 Distribution of visits over time

The detection of microlensing events is best done with uniform sampling. We request higher cadence at the beginning of the survey (until > 15 epochs are collected in r , g , and i bands), because microlensing events can be found only after it is found, which stars are constant. In order to achieve uniform cadence, it may be necessary to observe the field at airmass as large as 2.0.

3.8 Filter choice

The number of the monitored sources is the highest in r band. Slightly smaller number is in g band, and the third best filter is i . Hence, we request the relative number of epochs to be $4 : 2 : 1$ in r , g , and i bands, respectively. Having multi-band observations is important in order to characterize the properties of sources in microlensing events.

3.9 Exposure constraints

We request standard 2×15 s or 1×30 s visits. The total exposure time per visit is constrained by desired depth of a single visit. Saturation of brightest objects is not an issue because there are almost no events with sources saturated in standard LSST visits and if an event becomes brighter than saturation limit, then follow-up resources will provide adequate photometric coverage.

3.10 Other constraints

There are no other constraints.

3.11 Estimated time requirement

The exposure time (30 s) plus slew/settle and shutter open/close is only 35 s. The slew time is going to be relatively short. The closest field that is observed with standard Wide-

Fast-Deep cadence in `baseline_2018a` is separated by only 11.5° . More importantly, one of the Deep Drilling fields (namely R.A. = $23^h17^m33^s$, Dec. = $-63^\circ19'16''$) is located only 13.2° away. Observations of this Deep Drilling field give many chances to slew to the SMC field without too much overhead on slew and filter change. We estimate that typical slew and settle time will be 15 s and a quarter of the visits will require filter change, which takes 120 s. The average total time is 80 s per visit. The total time requested for 2000 visits is only 44.44 h or 0.18% of the total time available (24236 h).

Properties	Importance
Image quality	2
Sky brightness	3
Individual image depth	1
Co-added image depth	3
Number of exposures in a visit	3
Number of visits (in a night)	1
Total number of visits	1
Time between visits (in a night)	2
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

1. What is the effect of a trade-off between your requested survey footprint (area) and requested co-added depth or number of visits?

This proposal requests only a single pointing. If the center of this pointing is significantly offset from the SMC center, then high cadence in 2 or 3 fields would be required. In that case, the increase in the area covered does significantly increase the total number of events.

There is no constraint on co-added depth.

2. If not requesting a specific timing of visits, what is the effect of a trade-off between the uniformity of observations and the frequency of observations in time? e.g. a ‘rolling cadence’ increases the frequency

of visits during a short time period at the cost of fewer visits the rest of the time, making the overall sampling less uniform.

Uniform cadence is requested and is most advantageous for proposed science program. The increase of visit frequency (at the cost of lower frequency at other times) will only help if short-lasting caustic-crossing features are predicted, but in those cases follow-up resources should be used.

3. What is the effect of a trade-off on the exposure time and number of visits (e.g. increasing the individual image depth but decreasing the overall number of visits)?

A decrease in overall number of visits is not desirable, because it will delay the detection of the microlensing events. It will allow additional very faint events to be observed, but their value will be lower due to limiting depth of follow-up observations.

4. What is the effect of a trade-off between uniformity in number of visits and co-added depth? Is there any benefit to real-time exposure time optimization to obtain nearly constant single-visit limiting depth?

Only a single field is proposed here and uniform sampling in time is more important than uniform depth of each visit.

5. Are there any other potential trade-offs to consider when attempting to balance this proposal with others which may have similar but slightly different requests?

We expect that there will be other proposals that request observations of SMC and LMC (see Sec. 7 in Marshall et al. 2017). Most of the other proposals will probably put stronger requests on observing a large area of the Clouds at the expense of lower cadence. Our proposal is most beneficial at the center of SMC. We expect variability studies in SMC (including planetary transits) will be optimized towards the largest number of stars monitored, which is in accordance with plan proposed here. Observations in u , z , and y bands may be requested in other proposals, but these bands have low value for science program proposed here. If they are executed in addition to our program, then they will improve source characterization to small degree.

4 Performance Evaluation

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In our simulations of detection efficiency, we have included intensive photometric follow-up observations. The optimum follow-up would be uniform and 24-hour coverage of every on-going microlensing event with high photometric accuracy. SMC lies close to the South celestial pole and there is a limited number of observatories with good astronomical climate that can observe SMC. There is a large number of telescopes located in Chile, but they cover a narrow range of longitudes. Outside Chile, the only observatories with large aperture telescopes are Siding Spring Observatory (Australia) and South African Astronomical Observatory (South Africa). The number of clear nights and seeing are better for Chilean

observatories. Taking all these aspects into account, we divide follow-up observations into Chilean and non-Chilean. For Chilean observatories, we assume observations are taken when the SMC center is at the altitude $> 30^\circ$ and Sun is at the altitude $< -15^\circ$ as seen from Cerro Pachón. We select nights for which these conditions are fulfilled for at least 30 min. and assume uniform cadence of 1 h. To simulate the impact of clouds, we remove epochs for which there is no LSST observations (in any field) 1 h prior or after considered follow-up epoch. There are in total ten optical telescopes in Chile that have aperture of 4 m or larger. We assume that follow-up observations will be conducted using a ≈ 4 -m aperture telescope and the same exposure time as for LSST. The same accuracy should be achievable using longer (and still reasonable) exposure times on a 2-m class telescopes. To account for airmass, seeing, and sky transparency on photometric accuracy, we use the accuracy of the closest LSST observation with additional correction of $\delta m_5 = -0.53$ mag added to 5σ depth of LSST (for this we use the i -band observations in a few fields close to SMC), see Ivezić et al. (2018).

The potential follow-up telescopes outside Chile have smaller apertures and poorer weather conditions. We simulate these additional follow-up epochs assuming there is a single epoch per night and it is shifted by 12 h relative to observations in Chile. Additionally, we select half of the nights only. To obtain photometric accuracy of these data, we follow the same procedure as for Chilean follow-up observations.

For each event, the follow-up observations are assumed to start 12 h after the event detection and end $3t_E$ after the event peaks.

The above strategy leads to on average 1400 follow-up epochs for Chilean observatories over 10-month long season in `baseline_2018a` run. For non-Chilean observatories there are on average 120 follow-up epochs per season.

5 Special Data Processing

Describe any data processing requirements beyond the standard LSST Data Management pipelines and how these will be achieved.

No special data processing is needed.

6 References

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