Dynamic Follow-up of Transient Events with the LCOGT Robotic Telescope Network

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1 Introduction

The demands of astronomical observations have changed dramatically over recent years. Traditionally, an observer would personally visit a single telescope with a static target list, to observe for a contiguous block of time awarded 6 months in advance. Modern multi-year surveys are breaking this paradigm. They observe continuously, from both hemispheres on the ground and from space with a range of different survey strategies, and produce a continuous stream of discoveries via online alerts. Some require an immediate response in order to extract new science. Most surveys are designed to provide new target detections only and cannot usually provide comprehensive characterization or even classification. Follow-up teams have therefore been organized to provide additional observations, but it is generally impossible for them to provide a target list in advance and fixed blocks of telescope time are often disadvantageous and inefficient. Teams of observers are often needed, creating a huge overhead in travel costs. The Las Cumbres Observatory Global Telescope Network (LCOGT) is a new and unique facility designed to address this issue.

2 The LCOGT Network

LCOGT is a network of 12 robotic telescopes, geographically distributed in both latitude and longitude: 2×2m + 9×1m + 1×0.8m telescopes spread across 6 sites in both hemispheres. Telescopes are organized in clusters of between 1–3 at each site, and each aperture class of telescope supports an homogenous set of instruments and filters. The network is described in detail in [1]. During 2013, the 2m network was scheduled on legacy software, independently from the 1m network, but in the future all telescopes will be scheduled, crucially, *as a single facility*. This enables the maximum degree of flexibility in scheduling, allowing the network to compensate automatically for the loss of any site or individual telescope to weather or technical issues. It also brings new and unique science opportunities, being capable of targeting the same object from multiple sites, telescopes and instruments. In particular, with a multiple sites per hemisphere, greatly extended time series observations are possible at any cadence. For more details on the LCOGT Network Scheduler, see [2].

3 Exploiting Robotic Facilities for Astronomy

LCOGT has developed a web-based portal and Application Programming Interface (API) for the purpose of submitting observation requests. For large scale, highly responsive programs, efficiency and man-power limits make it desirable to have project-side software to compute the observations necessary for our science goals and interact with the LCOGT scheduler robotically. The system is designed to respond appropriately at any time to new survey alerts, without waiting for human approval.

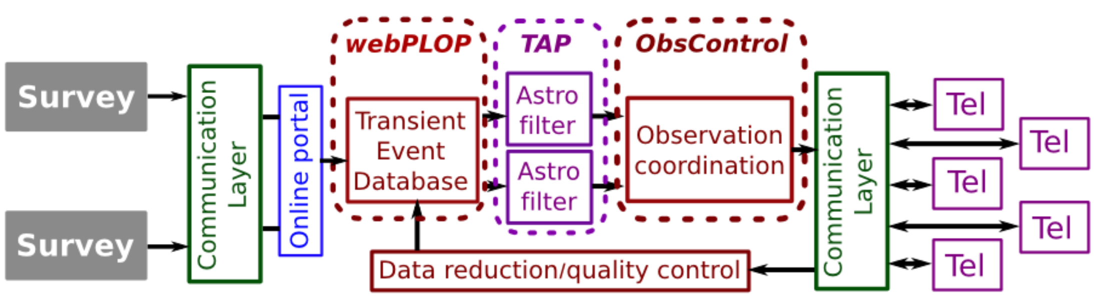

Figure 1: The outline of the robotic system designed to respond automatically to survey alerts and provide appropriate follow-up observations of targets identified to be high priority.

Figure 1 outlines the structure of this system. Its key features are i) survey alerts are gathered into a central database, ii) the alerts are classified and prioritized according to one or more filters designed to identify specific classes of events of astronomical interest, iii) selected targets trigger observation requests according to a pre-determined 'recipe', which may vary according to the stage of an event and/or its parameters measured at a given time, iv) the data taken are automatically reduced and v) the target is automatically re-evaluated in the light of the new information and the observing program adjusted as necessary. We have built a system, following this structure, which runs a large-scale robotic observing program designed to characterize microlensing events.

4 Microlensing Planet Detection

A microlensing event occurs when a foreground star (the 'lens') crosses the observer's line of sight to a background star (the 'source'). This causes the source to brighten gradually as the gravity of the lens bends light around it, towards the observer, fading back to its normal brightness as the stars move out of alignment over the course of days to months. If the lensing star hosts a planet, then this can provide additional magnification of the source star, called an 'anomaly', if the planet happens to be close to the Einstein radius (θ_E) of its host star at the time of the event. This radius, $\theta_E = \sqrt{(4GM_L/c^2)(D_{\mathrm{L}}^{-1} - D_{\mathrm{S}}^{-1})}$, is determined by the lens star mass (M_L) and the distances of the lens and source from the observer (D_{L} and D_{S}). These events are transient, so it is necessary to obtain immediate follow-up observations. Furthermore, anomalies can occur at any time and last anything from just minutes to days. Microlensing events therefore have to be monitored around-the-clock, but different stages require different densities of sampling, as illustrated by Fig. 2. The priorities can change at a moment's notice, particularly once an anomaly is detected. Two established surveys, OGLE [1] [3] and MOA [2] [4, 5], discover ~2000 microlensing events each year and provide prompt online alerts. Our RoboNet[3] [6] microlensing follow-up program employs not just the LCOGT telescope network but also the Liverpool Telescope, Canary Islands, Spain.

5 Responsive Automated Observation Control System

The observation control system consists of three automated stages (see Fig. 1):

[1] ogle.astrouw.edu.pl
[2] www.phys.canterbury.ac.nz/moa
[3] robonet.lcogt.net

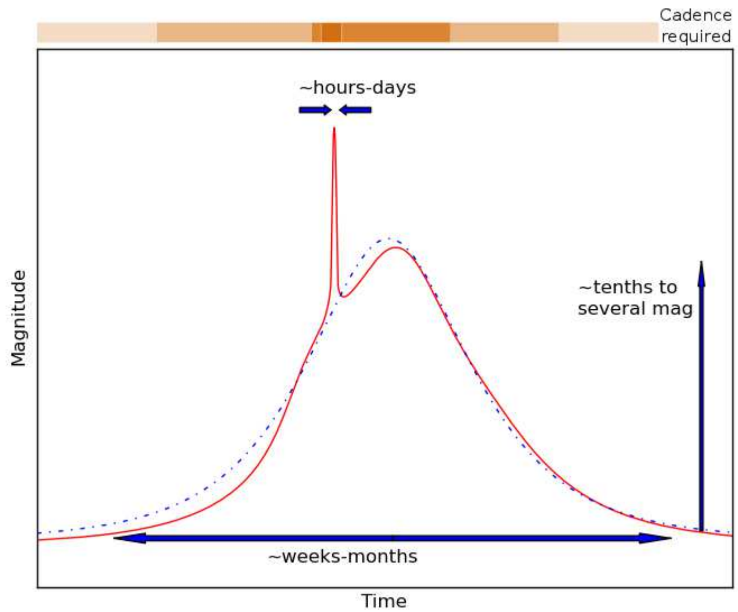

Figure 2: Schematic diagram of the light curve of a microlensing event. The density of shading of the bar at the top of the figure is directly proportional to the density of sampling necessary to properly characterize the critical stages of the light curve.

WebPLOP: the event database [7]:
This continuously harvests online alerts, downloading the location, finder chart and parameters of the initial model fit. It gathers all available light curve data by automatic query of the ARTEMiS system [8, 9], a public service that also provides alerts of anomalies. Updated data is gathered as the event progresses. This information is held in a database made publicly accessible through a web-based, interactive portal. WebPLOP performs its own model fitting procedure, but can also handle multiple 'opinions' on the same events from different sources, which feed into decisions on priorities for follow-up.

TAP: TArget Prioritization
In 2013 our team [10] developed a new algorithm to robotically prioritize events for follow-up. Typically ∼50–100 events are ongoing but at different stages at any one time, and require a range of observing cadence (see Fig. 2). The parallel observing modes available on the LCOGT network require a further degree of optimization. TAP reviews the WebPLOP database at regular intervals, and returns a list of events to be observed, including recommendations for exposure time and, wherever possible,

ensures that a given event is observed with consistent instruments to simplify data reduction. This enables TAP to implement a pre-determined 'observing recipe' which dictates what observations should be made at each stage of an event, as a function of its peak magnification, current brightness, location on sky and existence of anomalous features. The software runs at frequent intervals under the cron to ensure a rapid response to new alerts, and also updates a human-readable HTML version of its output to assist coordination with other observers.

ObsControl.
This acts to implement TAP's recommendations across the multiple telescope networks used by our program. In the 2013 season, while the LCOGT-network scheduler was at a primitive stage, it determined the optimum observing schedule for each of the 11 telescopes in use, factoring in hours of darkness, target visibility and telescope availability. These aspects continue to evolve to keep pace with the rapidly developing network-wide scheduler. ObsControl formulates and submits actual requests for observation using the different protocols currently required for the LCOGT-2m network, LCOGT-1m network and the Liverpool Telescope. The majority of the observations are conducted by the automated system, but there is also a web-based manual interface. ObsControl handles the download of the data obtained, which it filters through an in-built quality control process before preparing the data for automated pipeline reduction. All stages of our software maintain extensive, automated logging, crucial for both the identification and diagnosis of issues, and for evaluating the efficiency and effectiveness of its performance.

6 Conclusions

Figure 3 shows a sample of light curves obtained by our robotic follow-up program during the 2013 microlensing observing season. We observed 204 events in total, using 11 telescopes in multiple networks and achieved the dynamic, time variable cadence necessary to characterize these complex transients. This system demonstrated its ability to optimize a challenging observing program using the multiple modes of parallelization offered by LCOGT's telescope network.

This has clear applications to many other fields in astronomy. The same system structure could be generalized to include other instrument types (eg. spectrographs) and to implement 'observing recipes' optimized for other classes of target.

We thank the Qatar National Research Fund, member of Qatar Foundation, for support from QNRF grant NPRP-09-476-1-078.

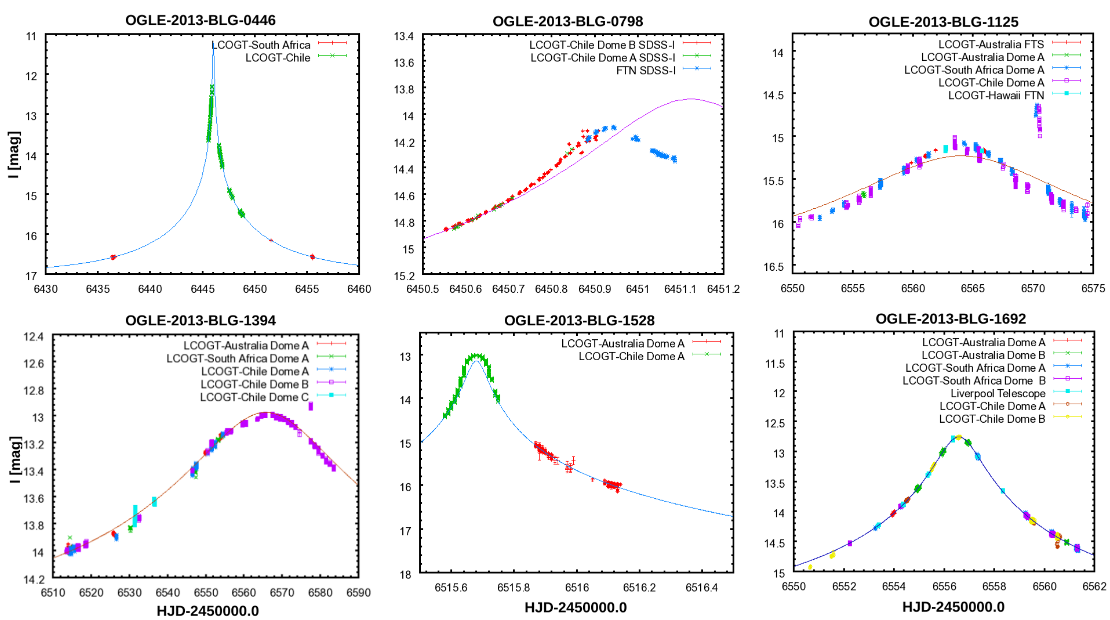

Figure 3: Sample of light curves obtained by our microlensing program in 2013, robotically coordinating 11 different telescopes.

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