Microlensing Recommendations for ZTF

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Microlensing Basics

Microlensing occurs when a foreground object (the lens), passes directly across the observer's line of sight to a background source star. The gravity of the intervening massive object bends the source's light, creating two images of the source and resulting in more of that star's light reaching the observer. As the proper motions of all three move in and out of alignment, the observer sees a characteristic gradual brightening and fading of the source, typically taking between 1-200 days (for a full discussion, see Gaudi 2010).

This technique has the unusual property of requiring no light to be received from the lens, yet it can reveal a great deal about that object. Microlensing is thus a useful tool for studying compact objects and extremely faint stars over great distances but has come into its own over the last two decades as a method of probing for exoplanets orbiting the lens. For galactic stellar lenses, microlensing's detection sensitivity peaks for planets at orbital separations between 1-10 AU. As such it serves to complement the discovery space of other planet hunting techniques, in particular transits and radial velocities, which are most sensitive to massive, close-in planets. Unlike those methods, however, the magnification during a microlensing event depends primarily on the projected separation of the lens and source. If a planet orbiting the lens happens to coincide with one of the images of the source during the event, the observer can detect its presence from an anomalous, additional brightening on top of the lensing lightcurve. The technique can be used to study binaries of all masses – in general, larger mass companions cause anomalies of longer duration.

Approximately 2000 microlensing events are discovered annually by surveys, notably OGLE[1], MOA[2], and most recently KMTNet[3], in the direction of the Galactic Bulge. As all but KMTNet are single-site surveys, their observations have traditionally been complemented with high cadence photometric follow-ups teams such as MicroFUN [PI: Gould], PLANET [PI: Beaulieu], MiNDSTEp [PI: Jørgensen] and RoboNet [PI: Street, Tsapras et al. 2009]. These teams have employed a range of geographically-distributed telescopes to ensure well sampled lightcurves are obtained for high-priority events, with great success: 43 planets have been published to date[4].

The need for follow-up teams is essential given the intrinsic nature of planetary anomalies. Because the duration of such anomalies scales as $m_p^{1/2} \times t_E$ (where m_p is the planetary mass and t_E is the Einstein angular radius crossing time, which is event dependent. The mean value is ~ 20 days in the GB), planetary deviations can last from a few hours for Earth-mass planets to few

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[1] http://ogle.astrouw.edu.pl/

[2] http://www.phys.canterbury.ac.nz/moa/

[3] http://kmtnet.kasi.re.kr/kmtnet-eng/

[4] http://exoplanetarchive.ipac.caltech.edu/

days for more massive bodies. These typical short duration events explain the need for continuous coverage of the event during its magnification.

Microlensing Observations

Microlensing observations generally focus on the Galactic Bulge (GB thereafter), where the optical depth tau, τ (i.e. the event probability per star) is the highest. However, even in this crowded region, this probability is still very low at $\tau \sim 10^{-6}$. Surveys sample the region following their own strategy depending primarily on the event occurrence, which is proportional to the number of stars (Poleski et al. 2016). Due to the relative high number of microlensing events that occur simultaneously during the season, follow-up teams have to decide which events to observe. Each team follows their own strategy, but they mainly focus on high magnification events, as they are the most sensitive to planets — as well as undergoing anomalous events.

As explained above, the nature of microlensing requires dense coverage for the modelers, although the event detection does not require hourly samples. Some points a night are sufficient to detect the vast majority of events. Because these events undergo heavy interstellar extinction, the vast majority of teams use NIR filters (I in general). However, some color information (V band for example — 1 observation every night) are welcomed, both for false alarm rejections and event characterization.

We are in the process of developing a machine learning algorithm that can detect microlensing events in wide-field surveys such as ZTF. Injecting microlensing parameters into flat lightcurves extracted from PTF, microlensing signals were simulated as they would have appeared in the PTF survey. Lightcurve statistics were calculated for these simulated signals, the majority of these parallel those calculated by PTF (metrics derived from Richards et al. 2011). The classifier was trained to differentiate between these simulated microlensing events and several hundred Cataclysmic Variables (CV thereafter), RR Lyrae variables, and constant stars. The classifier constructed a statistical parameter space, determining which statistics were more significant to differentiate between these sources and makes the class prediction depending on the statistics calculated from the inserted lightcurve.

The first test of the algorithm performance was conducted using half of the downloaded CV, half of the Lyrae, and half of the constant stars — as well as 150 simulated microlensing, for training the algorithm. An additional 150 microlensing events, as well as the remaining half of the CV, Lyrae and constant sources were inserted for testing. The performance of the classifier is displayed in Figure 1.

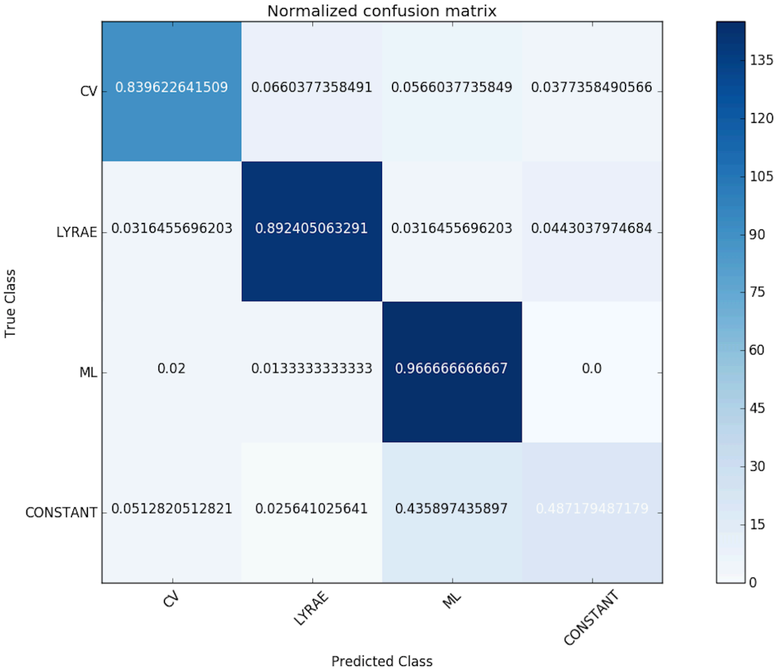
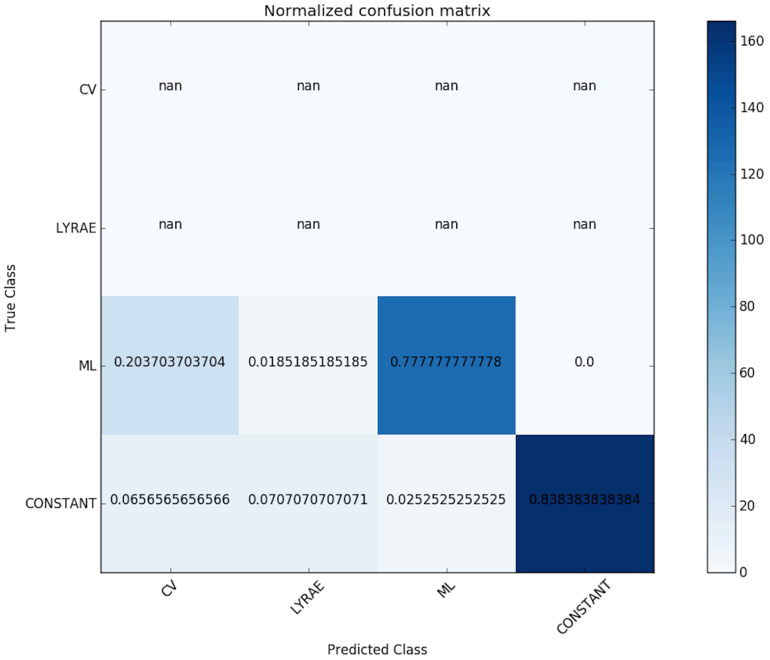


Figure 1: *Results from a random forest (RF) classifier designed to distinguish microlensing events from variable types that are the most common causes of false positives. By comparing the PTF-assigned class for each lightcurve with that predicted by the classifier, we can evaluate its success ratio for each type of variable.*



The algorithm performed well at differentiating between CV, Lyrae, and microlensing signals in the PTF database. However, it failed to classify constant sources efficiently — we suspect the reason being the low number of available constant lightcurves that were used for training (40 for training, 39 for testing). The second test conducted revolved around the microlensing events discovered during the OGLE II survey between 98’ and 2000 (~160). For this test all available CV, Lyrae and constant sources were used for training, as well as 150 simulated microlensing events. The results of the classifier is to the right.

Given that the microlensing signals used for training were simulated from PTF lightcurves, and those tested were from OGLE II, this test eliminates any bias in the metrics calculated given the different cadences and parameters of each survey. Given that ~3/4 of the tested OGLE II signals were classified correctly, we are confident the program could perform efficiently enough to detect any potential microlensing signals in the PTF database, as well as in the future with ZTF. As more classes and metrics are incorporated into the algorithm, we expect the detection efficiency to improve in accuracy.

Recommendations for Microlensing with ZTF

ZTF could add an unprecedented contribution to the microlensing field. First, thanks to its gigantic field-of-view, ZTF could conduct a GB survey using only one field. This field centered around (18h00h00, -30º00’00) will cover the regions with the highest rate of microlensing events within one image. This will lead to a very consistent dataset with uniform cadence for all events in the fields. Secondly, ZTF could conduct a microlensing search in regions neglected by other teams, like the Galactic Plane. Although the event rate in this region is lower given its lower stellar density, some events are still to be expected. In addition, it will be of great importance to demonstrate that microlensing occurs outside the GB, as that could influence the strategy undertaken by additional surveys, such as the LSST.

Finally, the US government does not yet have a microlensing survey in preparation for the WFIRST mission, which will require ground data to better characterize the field-of-view (extinction, stellar population, etc). For the microlensing observations, we recommend that ZTF observe one field in the GB with a cadence of at least 1 observation per night in the R/I filter, with an additional observation in the V band preferred to aid in identifying false-positives. This will ensure adequate sampling for event detection, which will in turn trigger follow-up observations in real-time by additional teams, such as our group at the Las Cumbres Observatory that has had great success through the use of the RoboNet project.

References

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