A real-time spectroscopic survey of 12,000 microlensed bulge stars: exoplanet characterization and bulge chemical evolution

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Background

Gravitational microlensing provides access to several relatively unexplored regimes of exoplanet science. In parallel, as in other gravitational lensing applications, microlensing provides natural telescopes for studying faint and otherwise unobservable sources. Microlensing is sensitive to planets with masses as low as that of the Earth, with projected separations from their host in the range ∼(1–10) AU. This corresponds to the region near and beyond the "snowline," where planet formation models predict that ice giants are created (Ida & Lin 2005). Current exoplanetary microlensing searches also probe exoplanet populations from the Solar neighborhood to the Galactic center, making microlensing the only technique that can presently measure the Galactic distribution of planets (Calchi Novati et al. 2015). Finally, since microlensing does not rely on the flux from the lensing object, it has begun to explore the reservoir of free-floating planets (Sumi et al. 2011) and can systematically study their frequency and mass function.

A microlensing event occurs when the light from a background "source" star is magnified by the gravitational potential of an intervening foreground "lens" system. Current photometric microlensing surveys, which monitor tens of square degrees toward the Galactic bulge with an $\lesssim$hourly cadence, detect ∼2200 events per year, with 90% of them reaching a peak magnitude of $I \leq 19$. Over the past 5 years, "2nd generation" microlensing surveys have been using global telescope networks to continually monitor the bulge during the microlensing bulge observing season (mid-February through early November for a telescope in the southern hemisphere) in search of light curve anomalies that reveal planets around the lens stars and yield the planets' masses and projected separations (Shvartzvald, et al. 2016). Current microlensing surveys discover of-order 10 planets a year, and as of the 2015 start of KMTNet, this is expected to rise to ∼60 planets per bulge season (Henderson, et al. 2014). From space, *Euclid* (launch 2020) and *WFIRST* (launch ∼2025) will use microlensing to complete the exoplanet census begun by *Kepler*, producing thousands of planet detections that will enable a more comprehensive understanding of the full scope of planetary system architectures throughout the Galaxy.

A fundamental shortcoming of microlensing-discovered lenses, however, is the degeneracy between the lens mass, the lens-source relative proper motion, and the distances to the lens and the source. In ∼30% of planetary events this degeneracy is partly removed by the measurement of orbital microlens parallax over the course of the event, and this fraction will increase substantially in the era of *Euclid* and *WFIRST*, for which the same lensing events will be monitored from space and from Earth from vantage points separated by ∼0.01 AU. However, current and future surveys do *not* systematically study the source stars, which are typically faint members of the Galactic bulge population, or directly measure their distances.

Proposed Project

We propose to obtain spectra of all ongoing microlensing events that are $I \leq 19$ with a ∼daily cadence using the SDSS multi-fiber BOSS spectrograph.

This constitutes ∼300 events at any given time during the bulge observing window. A five-year program will obtain spectra of ∼12,000 microlensing events, including ∼300 planetary in nature. The 12,000 spectra of lensed bulge stars will compare with the only 58 currently in existence (Bensby, et al. 2013), none of which are lensed by a system with planets. Spectroscopic follow-up of a statistically large sample of microlensing events is a new scientific frontier and would significantly improve our understanding of the lens and source populations. Here we briefly describe the most promising science drivers.

1) Source spectral type and distance: In microlens event modeling, it is typically assumed that the source resides in the Galactic bulge. While this is statistically reasonable, it can be a source of systematic uncertainty. This assumption directly impacts the distance derived for the lensing system and indirectly affects the determination of the mass of the lensing system, which itself requires a measurement of the source angular size (derived from its position on a CMD). The total integrated exposure time for each magnified star will be tens of hours, giving a very high S/N spectrum. This will allow for the secure identification of the source spectral type and thus the derivation of its distance. Not only will this provide the largest sample, by several orders of magnitude, of microlensing events with direct source distance measurements, but the source distance and spectral type together will also give a reliable measurement of its angular size.

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2) Light from the lens (and unrelated blends): The standard microlensing light curve model requires separate accounting for the flux of the source, which is being magnified, and the "blend" light contribution from all non-source stars in the PSF, including the lensing system itself. A precise measurement of the source versus the blend flux helps set constraints on the mass and spectral type of the lens. The time-variable spectrum during the event will help disentangle the flux contributions from the source, the lens, and ambient interloping blend stars not dynamically associated with the event, and do so much more precisely than is feasible with photometry alone.

3) Binary sources: A higher-order effect often imprinted on a microlensing light curve is the orbital microlens parallax. This is a result of the change in the lens-source relative proper motion over the course of the lensing event (in both magnitude and direction) due to Earth's orbit around the Sun. However, this effect can sometimes be mimicked by "xallarap," the orbital motion of a source star that happens to be in a binary. High-cadence spectroscopy will provide the radial velocity of the source, enabling the breaking of this degeneracy.

4) Metallicity distribution and ages of bulge stars, and bulge formation history: The high S/N integrated spectrum will allow for the first large systematic study of the elemental abundances of main-sequence stars in the Galactic bulge, which cannot be explored without the lensing magnification. Bensby, et al. (2013) applied this technique to 58 microlensed bulge stars, and found that all of them are turnoff or subgiant stars, permitting also an age estimate. The source stars of typical lensing events have baseline I-band magnitudes of 19–21, corresponding to G–K stars at the distance of the bulge. The combination of the lensing magnification and a spectrum with tens of hours of integrated exposure time is the only way of studying the individual dwarf stars of this population in detail. APOGEE has found metallicities and ages for $\sim 10^4$ giant stars in the bulge (Ness et al. 2015). However, processes in giants may erase some original abundance signatures, line blending at high metallicities is a problem, and there has been a tension between analyses based on giants vs. microlensed dwarfs, e.g. regarding the presence of young stars in the bulge. An independent probe from a comparably sized sample of main-sequence stars is thus desirable.

5) Rotation of bulge stars: The Maoz-Gould effect (Maoz & Gould 1994), which has hitherto not been measured, occurs when the magnification field varies on the scale of the source size. It induces shifts in spectral lines since different parts of the source, with different radial velocities, are being magnified unequally (analogous to the Rossiter-McLaughlin Effect during exoplanet transits). In addition to giving an independent measure of the Einstein radius for these events, this will allow for the study of stellar rotation in the bulge populations.

6) Atmospheric transmission spectroscopy of a planet in a lens system: During an event it is possible for the light from the source to pass through the atmosphere of a planet in the lens system. Continuous spectroscopic monitoring (during the night in the western hemisphere) will increase the probability of obtaining spectra during a caustic crossing, when the magnification is particularly high (with magnifications in the tens to hundreds, sometimes brightening a source on hour timescales to 12–15 mag). During such a caustic crossing the lensed images straddle the planet, thus boosting the chances of acquiring a planetary transmission spectrum. Our team is currently studying the feasibility of detecting such a transmission spectrum. If such measurement is feasible we will plan a sub-survey with quasi-continuous coverage, which would represent a revolutionary venture for studying the atmospheres of distant, cold exoplanets.

Hardware requirements

The Galactic center is maximally visible from the southern hemisphere, so we advocate using the 2.5m Dupont telescope at LCO in Chile, with an upgraded version of the BOSS spectrograph (currently at APO). The region of the bulge with a high lensing rate covers $\sim$40 deg^2. The 3° diameter field-of-view of BOSS is thus capable of monitoring this region with only $\sim$7 pointings. We will use 30–100 fibers in each pointing, with 20 min exposures, to cover all ongoing events brighter than $I = 19$. The proposed program will thus use 2.5 hrs a night during bulge season. The remaining fibers can be used for other bulge and Galactic center programs. Efficient observations and the regular introduction of newly discovered events into the monitored sample advocate for robotic fiber positioners working on the timescale of minutes.

References

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