Confirming Black Hole Candidate Microlensing Events
MACHO-96-BLG-5 and MACHO-98-BLG-6

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Summary
Stellar-mass black holes (BHs) are predicted to be abundant in the Milky Way (N= 10^4–10^9) but only a few dozen have been detected observationally, all of which are in binary systems and typically actively accreting.\(^1\)\(^-\)\(^3\) Isolated BHs have yet to be detected. One method for attempting to detect isolated BHs is via gravitational microlensing: when a BH passes in front of a star and briefly magnifies the star’s observed brightness.\(^4\)\(^-\)\(^6\) However, during a microlensing event, there is no certain method for determining, from photometry alone, whether the lens is a BH or another star. Eventually, the source and lens will separate and a non-black-hole lens should become observable. If the lens is not an isolated BH, then the source and lens should have moved apart enough to be resolved with high-resolution imaging. We present follow-up observations of two microlensing events, MACHO-1996-BLG-5 (MB 96-5) and MACHO-1998-BLG-6 (MB 98-6), which were first observed in 1996 and 1998, respectively, and are both long-duration events with a high probability that the lens is a black hole.\(^7\)\(^-\)\(^9\) The closest projected approach between the source and lens was over 20 years ago. We observed the candidates and found both of them to potentially be stellar-mass black holes.

New Images
Using infrared adaptive optics images from the W. M. Keck Observatory, we observed the candidates in 2016 July. No new sources were found within 0.3 arcseconds of the lensed source, a rational separation considering the maximum possible relative proper motion of the lens and source. The images are shown in Figure 1.

Figure 1 – Top: Microlensing candidates MB 96-5 (left) and MB 98-6 (right). The sources are shown in the center of the images. Bottom: Residual images for both candidates. All stars detected by Starfinder are marked by open circles. No new sources were detected. For MB 96-5, the nearby star, marked about -0.2 arcseconds to the East, is a previously known source detected during the original microlensing event.

Image Analysis
Infrared images were obtained on 2016 July from W.M. Keck Observatory using adaptive optics with the NIRC2 instrument.

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Completeness
In order to determine the characteristics of an undetectable stellar lens, we planted artificial stars of different brightnesses at each pixel within a radius of 0.3 arcseconds of each target source. Analyzing the undetected planted stars gave us limiting magnitudes and corresponding completeness curves, shown in Figure 2. From these limiting magnitudes, we used synthetic isochrones from a combination of stellar evolution and atmosphere models to determine the upper-limit masses. We excluded magnitudes brighter than the respective source.

Results
Given the MB 96-5 constraints on the relative proper motion between the source and the lens (Figure 3, blue region), we rule out all stellar models with M>0.09 M\(_\odot\) for lens distances >0.5 kpc and an age of 100 Myr. We note that for larger distances and smaller proper motions, the source and lens would remain blended, even 20 years later; however, the probability of such a low proper motion is small. We plan to further constrain a luminous lens contribution in this case using multi-band photometry in the future. For MB 98-6, a number of stellar lens scenarios are still allowed with masses from 0.08 – 2.0 M\(_\odot\) for the same age.

Figure 2 – Completeness curves for MB 96-5 (top) and MB 98-6 (bottom). By finding where the detection completeness for a giving magnitude goes below 0.95, we determined the magnitude range of a stellar lens undetectable by Starfinder. These magnitude ranges gave us our upper limits to the mass of an undetectable stellar lens.

Figure 3 – The ranges of masses, distances, and proper motions of possible stellar lenses undetected by Starfinder for MB 96-5 (left) and MB 98-6 (right). These ranges were determined using synthetic isochrones for the age of 100 Myr. The blue shaded regions show the allowed ranges determined by assuming a source distance of 10 kpc and using the constraints of Bennett et al. 2002 on the transverse relative motion. The gray shaded regions show the areas of total separation within 50 mas, where further analysis is needed to constrain the masses of possible compact lenses. A star marker represents a stellar lens that matched a limiting magnitude at a given distance and proper motion. A black marker represents a lens with no matches, which could therefore be a black hole or other compact object.

Conclusions
We increase the likelihood that the two microlensing events MB 96-5 and MB 98-6 are black holes through our non-detection of a luminous lens resolved from the source nearly 20 years after the original event. Currently, for MB 98-6, a large range of stars are still allowed. However, we may be able to further rule those out using color information and improved estimation of the point spread function. In order to provide even more constraints, further studies of these events and their respective source and lens distances would give valuable information and clarify the event dynamics. In order to refine constraints on the mass of the lens, particularly at low separations (i.e. low proper motions), we plan to re-model multi-band photometry including blending and color information from multi-band high-resolution images.

Acknowledgements
The data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

References
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