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RECENZJA PRACY DOKTORSKIEJ MGR PRZEMYSŁAWA MROZA
"ASTROPHYSICAL APPLICATIONS OF GRAVITATIONAL MICROLENSING IN THE MILKY WAY"

Ponieważ praca doktorska mgr Mroza napisana jest po angielsku, główna część poniższej recenzji napisana jest w języku angielskim.

General Comments:

The title of this Ph.D. Thesis, while fairly broad, properly reflects its content. The scientific problems posed and solved are interesting and sufficiently significant to warrant inclusion in a Ph.D. Thesis. The majority of the Thesis, besides a short "Streszczenie", is written in English, which is natural given that many of the results presented have been already published, in English, in refereed journals, including *Nature, AJ,* and *A&A*. The PhD candidate was the first author on these papers, and they are already being well cited. It is clear from the material presented in this Thesis what the specific contribution of mgr Mróz was to the data collection and reduction. The candidate participated in all stages of the work presented, including taking data, reducing the data, analyzing and interpreting the results, and preparing these results for publication. The structure of the Thesis is logical and clear, and it was a pleasure to read it.

Description of the content of the Thesis and evaluation of results presented:

The Ph.D. Thesis of mgr Mróz consists of two major parts. In the first part of his Thesis, he focused on searching for and constraining the frequency and nature of "rogue" (free-floating) planets in the Milky Way. The existence of some such planets, gravitationally unattached to any stars, is predicted to naturally result from the process of formation of planetary system, but with a very large uncertainty on how many such planets there are, and how massive they would be. While "rogue" planets are likely to be extremely cold and therefore faint, rendering them practically invisible to traditional methods of astrophysical detection, they can be discovered using gravitational microlensing via their light-bending gravity. Mgr Mróz analyzed OGLE multi-year data to show that, among other results, Jupiter-mass free-floating planets are much less common then previously claimed. In the second part of his Thesis, mgr Mróz used long-term photometric observations of the Galactic bulge by the OGLE survey to select a homogeneous sample of 8,000 gravitational microlensing events to create the largest and the most accurate microlensing optical depth and event rate maps of the Galactic bulge. Both parts of the Thesis, as discussed in more detail below, present new and very significant contributions to astrophysics.

Chapter 1, Introduction, presents the history and methods of the field of microlensing, going back to Einstein (1916), and then the modern era of that field, pioneered by Paczyński (1986). This chapter was very well written and did an excellent job of presenting the increasingly complex situations one can encounter when working in this field: point-source point-lens microlensing; extended source microlensing; microlens parallax events; binary lens microlensing; planetary microlensing; and finally microlensing optical depth and event rate. Since all of these concepts are important for the work presented in this Thesis, having a compact yet informational Introduction was helpful in reading the following Chapters.

The very brief Chapter 2 presents the history and current status of the Optical Gravitational Lensing Experiment (OGLE), again presenting information helpful when reading the rest of the Thesis.

Chapters 3 and 4 present results related to the discovery and characterization of free-floating planets. In Chapter 3, mgr Mróz finally addresses the findings of Sumi et al. (2011), who, based on analysis of microlensing data from the MOA experiment, claimed that the frequency of free-floating Jupiters is very large indeed: roughly two such planets for each main sequence star! However, results presented in Chapter 3 clearly show that Sumi et al. (2011) claim was incorrect, as the numerous, very short timescale (1-2 days) microlensing events produced by such planets would have been seen in high cadence OGLE data, but none were detected. Instead, no excess of events with timescales in this range was found (Figure 3.6), with a 95 percent upper limit on the frequency of Jupiter-mass free-floating or wide-orbit planets of 0.25 planets per main-sequence star. However, few possible ultrashort-timescale events (with timescales of less than half a day) were discovered, which may indicate the existence of Earth-mass and super-Earth-mass free-floating planets, stimulating further search for such events.

I find the results presented in Chapter 3 extremely interesting and compelling, and they clearly show that the extraordinary claims of Sumi et al. (2011) (a paper that has been cited more than 300 times!) were simply incorrect.

In Chapter 4, motivated by the discovery of few ultra-short timescale microlensing events in 2010-2015 OGLE data, mgr Mróz decided to search for such events in the 2016 observing season data, supplementing OGLE data with KMTNet data (which has three Southern Hemisphere telescopes widely distributed in longitude, which is needed to study short timescale events). One such event was indeed found, with a timescale of about 0.3 days, most likely caused by a Neptune-mass free-floating or wide-orbit planet. Another similar event was discovered in 2017 data. Both of these events showed very strong finite source effects (a situation where the angular size of the star being lensed is much larger than the angular size of the Einstein ring), which results in small magnification events, most likely missed in previous searches. This led to re-analysis of archival data and the discovery of the third possible ultra short-timescale event in the 2012 OGLE data, with a timescale of only 0.15 days, which could be due to microlensing by an Earth-mass object in the Galactic disk. These three events were then studied in detail using a variety of sophisticated procedures.

Here again I find results presented in Chapter 4 most interesting and compelling, clearly showing that there is a likely population of small-mass, free-floating planets, which can be discovered and further characterized using microlensing. This has clear relevance for our understanding of planetary system formation, and also for future ground-based and space-based microlensing experiments, including NASA flagship mission WFIRST.

Finally, Chapter 5 presents the largest and the most accurate microlensing optical depth and event rate maps of the Galactic bulge, based on a homogeneous sample of 8,000 events discovered by OGLE. In my opinion that Chapter alone, somewhat extended, would make a very interesting Ph.D. Thesis. Having been involved in the very first measurement of the optical depth for microlensing, based on nine events (Udalski et al. 1994), I am most impressed by the data and sophisticated analysis presented in Chapter 5. These new maps, apart from testing the Milky Way models, have numerous other applications, such as aiding in measurement of the initial mass function, and they help to inform planning of the future space-based microlensing experiments by revising the expected number of events. The results presented in Chapter 5 have now been submitted for publication and also posted on astro-ph preprint archive.

In summary, I am most impressed with the various results presented by mgr Mróz in this Ph.D. Thesis. While I am not anymore scientifically active in the field of microlensing, I was aware (and doubtful) of extraordinary claims made by Sumi et al. (2011), and it was scientifically satisfying to see them put to rest by the excellent analysis presented here. It was also gratifying to see the search for ultra-short microlensing events yielding such interesting results. However, I am even more impressed by the Galactic bulge microlensing optical depth results from Chapter 5, as over the years numerous papers did not properly take into account various effects now properly modelled by mgr Mróz. It will be very hard for anybody to improve on these results for years to come.

Comments and suggestions:

I did not find any significant errors in this Thesis. However, I do have several comments/suggestions and questions for the Ph.D. Candidate:

1. There has been now a number of bright microlensing events discovered outside the Galactic bulge, including events in the anti-center direction such as TCP J05074264+2447555 (Jayasinghe et al. 2017b) or ASASSN-V J044558.57+081444.6 (Jayasinghe et al. 2017a). In principle, such events should be rare, as discussed in Gaudi et al. (2008). Please comment and discuss the prospects for measuring the microlensing optical depth across the whole sky.

2. I was quite intrigued by Figure 5.15 (page 115) showing mean timescales of microlensing events as a function of Galactic longitude and latitude. However, I am somewhat confused by the written explanation for the observed asymmetry in Galactic longitude: "This asymmetry stems from the fact that the Galactic bar is slightly inclined .."—the Galactic bar is significantly ($\sim 20\,\mathrm{deg}$) inclined to the line of sight, see, e.g., Stanek et al. (1997).

3. On page 89, it is not historically accurate to say "These first measurements of the optical depth led to the realization ... that the inner regions of the Milky Way have a bar-like structure elongated along the line of sight (Paczyński et al. 1994; Zhao et al. 1995)." There was earlier, strong evidence for the Galactic Bar from a number of different methods, including Galactic bulge red clump stars observed by OGLE-I (Stanek et al. 1994), as discussed in Paczyński et al. (1994).

4. Very minor comment: showing the map of the Earth in Figure 4.2 adds very little value to Chapter 4.

Conclusions (in Polish):

Przedstawioną rozprawę oceniam bardzo wysoko. Autor uzyskał oryginalne i wartościowe wyniki, w obu częściach pracy. Stwierdzam, że przedstawiona rozprawa spełnia wszelkie ustawowe oraz zwyczajowe wymogi stawiane kandydatom do stopnia doktora. Wnoszę więc o dopuszczenie mgr Przemysława Mroza do dalszych etapów przewodu. Wnioskuję ponadto o uznanie pracy za wyróżniającą—w ciągu ostatnich 20 lat byłem promotorem lub recenzentem ponad 20 prac doktorskich, i uważam pracę mgr Mroza jako jedną z najlepszych w tej wyborowej grupie.

K. Z. Stanek

30 czerwca 2019