New Self-lensing Models of the Small Magellanic Cloud: Can Gravitational Microlensing Detect Extragalactic Exoplanets?

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Abstract

We use three-dimensional distributions of classical Cepheids and RR Lyrae stars in the Small Magellanic Cloud (SMC) to model the stellar density distribution of a young and old stellar population in that galaxy. We use these models to estimate the microlensing self-lensing optical depth to the SMC, which is in excellent agreement with the observations. Our models are consistent with the total stellar mass of the SMC of about $1.0 \times 10^8 M_\odot$ under the assumption that all microlensing events toward this galaxy are caused by self-lensing. We also calculate the expected event rates and estimate that future large-scale surveys, like the Large Synoptic Survey Telescope (LSST), will be able to detect up to a few dozen microlensing events in the SMC annually. If the planet frequency in the SMC is similar to that in the Milky Way, a few extragalactic planets can be detected over the course of the LSST survey, provided significant changes in the SMC observing strategy are devised. A relatively small investment of LSST resources can give us a unique probe of the population of extragalactic exoplanets.

Key words: gravitational lensing – micro – Magellanic Clouds – planets and satellites: detection

1. Introduction

Since the detection of the first exoplanets (Wolszczan & Frail 1992; Mayor & Queloz 1995) over 20 years ago, there is growing evidence that exoplanets are ubiquitous in the Milky Way (e.g., Mayor et al. 2011; Cassan et al. 2012; Howard et al. 2012; Anglada-Escudé et al. 2016). However, most of the known extrasolar planets are found in the solar “neighborhood” within $\sim 1$ kpc of the Sun, and current empirical constraints on the planet abundance in different environments are weak (e.g., Penny et al. 2016). The fundamental cause of this bias toward nearby exoplanets is the fact that most planet-detection techniques rely on the detection of the host light. Since the gravitational microlensing signal does not depend on the brightness of the host, it is one of the techniques that are sensitive to distant planets, both in the Galactic disk and bulge (Mao & Paczynski 1991; Gould & Loeb 1992).

The detection of extragalactic exoplanets is currently even more challenging. Exploring the ideas of Covone et al. (2000) and Baltz & Gondolo (2001), Ingrosso et al. (2009) discussed the possibility of detecting extrasolar planets in M31 using microlensing. Because individual source stars in M31 cannot be resolved by ground-based telescopes, only the brightest sources (i.e., giants) can give rise to detectable microlensing events. Ingrosso et al. (2009) found that, owing to a large angular size of sources, the planetary signal in the majority of events would be “blurred” by the finite-source effects. They estimated that planetary deviations can be discovered only in a few percent of detectable events. Pixel lensing surveys of M31 discover only a few events annually (Calchi Novati et al. 2005; de Jong et al. 2006). On the other hand, it has been shown that the Large Synoptic Survey Telescope (LSST)-like survey has the potential to discover transits of Jupiter-sized planets in the Magellanic Clouds (Jacklin et al. 2015; Lund et al. 2015). It would be nearly impossible, however, to confirm such planets with radial velocities, even with future 30 m class telescopes.

The Small Magellanic Cloud (SMC) has been the target of microlensing surveys since the 1990s, when—following the idea proposed by Paczynski (1986)—three groups (OGLE: Udalski et al. 1993; MACHO: Alcock et al. 1993; EROS: Aubourg et al. 1992) began the search for dark matter in the form of massive compact halo objects (MACHOs).

The most recent results from EROS (Tisserand et al. 2007), OGLE-II (Wyrzykowski et al. 2009; Wyrzykowski et al. 2010), and OGLE-III (Wyrzykowski et al. 2011a, 2011b) provided strong upper limits on the MACHO content in the Milky Way halo: less than 9% of the halo is formed of MACHOs with mass below $1 M_\odot$ (the limit is even stronger for lower masses). On the other hand, current microlensing results cannot exclude MACHOs more massive than several $M_\odot$. Wyrzykowski et al. (2010, 2011b) measured the microlensing optical depth of $\tau_{\text{O-II}} = (1.55 \pm 1.55) \times 10^{-7}$ and $\tau_{\text{O-III}} = (1.30 \pm 1.01) \times 10^{-7}$ toward the SMC in the OGLE-II and OGLE-III fields, respectively.

Only five bona fide microlensing events in the SMC have been reported so far, and most (if not all) of them are believed to be due to self-lensing, meaning that both the lens and the source belong to the SMC (Sahu 1994). One event, OGLE-2005-SMC-001, can be likely attributed to a halo lens, although the SMC lenses were not definitively ruled out (Dong et al. 2007). The microlensing optical depth and event rate in the SMC are larger than in the Large Magellanic Cloud (LMC), because the former is elongated nearly along the line of sight.

Various authors calculated the SMC self-lensing optical depth, usually based on simple analytical approximations of the number density of stars. Palanque-Delabrouille et al. (1998) and Sahu & Sahu (1998) reported values in the range $(1.0-5.0) \times 10^{-7}$. Graff & Gardiner (1999), using $N$-body simulations of the SMC, found a lower value of $0.4 \times 10^{-7}$.

In the recent work by Calchi Novati et al. (2013), the average optical depth of $0.81 \times 10^{-7}$ and $0.39 \times 10^{-7}$ was found, toward OGLE-II and OGLE-III fields, respectively.

However, the SMC has an irregular structure, which is difficult to model with analytic approximations (see Section 2). In this paper, we use three-dimensional distributions of classical Cepheids (Jacyszyn-Dobrzeniecka et al. 2016) and...
RR Lyrae stars (Jacyszyn-Dobrzeniecka et al. 2017), based on new observational results from the OGLE survey (Soszyński et al. 2015, 2016), to model the density distribution of the SMC and calculate the self-lensing optical depth and event rates (Section 3). We also estimate the total stellar mass of the SMC. We show that the LSST-like survey of the SMC is able to discover 20–30 microlensing events annually, some of which should have planetary anomalies, provided that significant changes of the observing strategy are devised (Section 4).

2. Model

2.1. Structure

We assume that the stellar density distribution is the sum of two components: a young population, which follows the spatial distribution of classical Cepheids, and an old population, tracing the three-dimensional distribution of RR Lyrae stars. Both classical Cepheids and RR Lyrae stars are standard candles and have been recently used to map the structure of the SMC (Jacyszyn-Dobrzeniecka et al. 2016, 2017; Deb 2017; Ripepi et al. 2017; Muraveva et al. 2018 and references therein).

Classical Cepheids form a non-planar, extended structure. The galaxy is stretched to nearly 20 kpc and elongated almost along the line of sight (Jacyszyn-Dobrzeniecka et al. 2016; Scowcroft et al. 2016). The shape of the young population is not regular and can be best described as an extended ellipsoid with additional substructures.

RR Lyrae stars follow much more regular distribution without any substructures and asymmetries. The spatial distribution of the old population can be approximated as a triaxial ellipsoid with mean axis ratios 1:1.10:2.13, also elongated along the line of sight (Jacyszyn-Dobrzeniecka et al. 2017; see also Deb 2017; Muraveva et al. 2018).

We approximate both distributions using a Gaussian mixture model, which is the sum of Gaussian distributions with unknown parameters and weights. The model fitting is performed with the expectation-maximization algorithm (Dempster et al. 1977). For both young and old population, we use 32 Gaussian components, which accurately describe the spatial structure of both Cepheids and RR Lyrae stars. We assume, following Bekki & Chiba (2009) and Calchi Novati et al. (2013), that the young population comprises 40% of the total stellar mass of the galaxy.

The microlensing optical depth is directly proportional to the total stellar mass of the SMC, which is not well constrained. Following Bekki & Chiba (2009) and Calchi Novati et al. (2013), we assume $M_\odot = 1.0 \times 10^5 M_\odot$ throughout the paper, but one should keep in mind that all derived optical depths scale as $(M_*/10^5 M_\odot)$. We find that $M_*/1.0 \times 10^5 M_\odot$ reproduces well the observed microlensing optical depth toward the OGLE fields, providing an independent estimate of the stellar mass of the SMC. Stanimirović et al. (2004) report the total stellar mass of $1.8 \times 10^8 M_\odot$ (within a radius of 3 kpc), but van der Marel et al. (2009), based on the analysis of the same data set, claim a total stellar mass of only $0.31 \times 10^9 M_\odot$.

2.2. Kinematics

The kinematics of the SMC is not well measured (van der Marel et al. 2009). The mean systemic velocity of the SMC is 230 km s$^{-1}$ in the east direction and 330 km s$^{-1}$ in the south direction (Kallivayalil et al. 2013) relative to the Sun, based on the multi-epoch data from the Hubble Space Telescope. This is consistent with a recent analysis based on Gaia data release 1 (van der Marel & Sahlmann 2016). The old and intermediate stellar populations do not show any evidence for systematic rotation. For example, Harris & Zaritsky (2006) found that velocities of red giant stars are randomly distributed without large velocity gradients (with a dispersion of $27.5 \pm 0.5$ km s$^{-1}$). Velocities of young stars (Evans & Howarth 2008) show some evidence of systematic rotation (with a gradient of $26.3 \pm 1.6$ km s$^{-1}$ deg$^{-1}$). However, the direction of the maximum velocity gradient found by Evans & Howarth (2008) is different from that measured from HI observations (Stanimirović et al. 2004).

For the old population we assume a Gaussian distribution of velocity components with dispersions of 30 km s$^{-1}$ in both directions (N and W). Because the kinematics of the young population is not well known, we consider two models. In the “slow model” we assign random velocities from the Gaussian distribution with the dispersion of 30 km s$^{-1}$ (without rotation). In the “fast model” we introduce the rotation around the axis $\omega = (\sin PA, \cos PA, 0)$, which is perpendicular to the direction of the maximum radial velocity gradient found by Evans & Howarth (2008) and to the line-of-sight direction. The Cartesian coordinate system has the origin in the center of the mass of young population and its versors are defined as in Jacyszyn-Dobrzeniecka et al. (2016). Here, PA = 126$^\circ$ is the position angle of the maximum velocity gradient line from Evans & Howarth (2008). We assume that the rotation velocity is increasing linearly up to 60 km s$^{-1}$ with a turnover radius at 3 kpc, and we add random components with the dispersion of 30 km s$^{-1}$ (Stanimirović et al. 2004; Evans & Howarth 2008).

2.3. Initial Mass Function and Isochrones

We assume a Kroupa (2001) initial mass function with slopes 0.3 for brown dwarfs ($0.01 < M/M_\odot < 0.08$), 1.3 for low-mass stars ($0.08 < M/M_\odot < 0.5$), and 2.3 for high-mass stars ($0.5 < M/M_\odot < 150$). Brown dwarfs constitute 37% of all objects (about 5% of the total stellar mass). The mean mass is $0.38 M_\odot$, and so the number of stars in our fiducial model is $0.63 M_\odot/0.38 = 1.66 \times 10^9$. Masses of stellar remnants are calculated following the approach of Gould (2000) and prescriptions of Mróz et al. (2017).

To estimate the number of sources that could be monitored by a given survey, we generated theoretical isochrones for 200 Myr (young population) and 10 Gyr (old population) for the SMC metallicity ($Z = 0.004$) using PARSEC-COLIBRI models (Marigo et al. 2017). We assume the foreground reddening of $E(V - I) = 0.04$ (Haschke et al. 2011).

3. Microlensing Predictions

3.1. Optical Depth

The microlensing optical depth toward a given source located at a distance $D_S$ is (Kiraga & Paczynski 1994)

$$\tau(D_S) = \frac{4\pi G}{c^2} \int_0^{D_S} \rho_L(D_L) \frac{D_L(D_S - D_L)}{D_S} dD_L,$$

Here, $D_L$ is the distance to the lens and $\rho_L$ is the density of lenses. In theory, the optical depth depends only on the mass distribution and is independent of other model assumptions.
Optical depth and event rates scale with the total stellar mass of the SMC $M_\ast$ as $(M_\ast/10^9 M_\odot)$. Parameters are averaged over sources brighter than $I = 21$ (OGLE), $r = 24.7$ (LSST), or all sources, Wyrzykowski et al. (2010) found $\tau_{\text{OGLE}} = (1.55 \pm 1.55) \times 10^{-7}$ and $\Gamma_{\text{OGLE}} \approx 5.6 \times 10^{-7}$ yr$^{-1}$ in OGLE-II fields. Wyrzykowski et al. (2011b) measured $\tau_{\text{O3-II}} = (1.30 \pm 1.01) \times 10^{-7}$ and $\Gamma_{\text{O3-II}} \approx 4.4 \times 10^{-7}$ yr$^{-1}$ in OGLE-III fields.

3.2. Event Rate

The differential event rate toward a given source is (Batista et al. 2011; Clanton & Gaudi 2014)

$$\frac{d^4 \Gamma}{dD_E dM_L d^2 \mu} = 2R_E v_{\text{rel}} n(D_L) f(\mu) g(M_L),$$

where $R_E = \sqrt{\frac{4GM_\ast (D_3 - D_\ast)}{c^2}}$ is the physical Einstein radius, $M_\ast$ is the lens mass, $n(D_L)$ is the local number density of lenses, $v_{\text{rel}} = |\mu| D_L$ is the lens-source relative velocity, $f(\mu)$ is the two-dimensional probability density for a given lens-source relative proper motion $\mu$, and $g(M_L)$ is the mass function. The total event rate can be obtained by integrating Equation (2) and averaging over all sources. Equation (2) can also be used for generating a random ensemble of microlensing events from our model. The procedure is described meticulously by Clanton & Gaudi (2014). In short: (1) We draw a random source located at distance $D_3$ and equatorial coordinates ($\alpha$, $\delta$) from our fiducial distribution. (2) We draw a random lens at distance $D_L$ from the range $[0, D_3]$ from the density distribution in the given direction $n(D_L, \alpha, \delta)$. (3) We assign random velocities of the lens and the source from Gaussian distributions and calculate the relative velocity $v_{\text{rel}}$. (4) We draw a random lens mass $M_L$ from the mass function (taking into account stellar remnants). Mass functions of young and old stellar populations are slightly different, but this effect has negligible impact on the calculated timescales. (5) We evaluate the Einstein radius $R_E$ and the event timescale $t_E = R_E / v_{\text{rel}}$. For each event we assign a weight $w = R_E v_{\text{rel}}$. We then estimate the mean timescale from $\langle t_E \rangle = \sum w t_E / \sum w$. The mean event rate is simply

$$\Gamma = \frac{2}{\pi} \frac{\tau}{\langle t_E \rangle}.$$
slightly longer than the mean timescales of events (67 ± 36 days) found by Wyzykowski et al. (2010, 2011b). Figure 3 shows the distribution of event timescales in fast and slow models. On average, timescales are ~3 times longer than those observed toward the Galactic bulge. The mean angular Einstein radius in the “fast” model is equal to 60 μas (with a 68% confidence interval of 24–96 μas). Since the typical angular radius of the solar-like main-sequence sources in the SMC is ~0.07 μas, the finite-source effect does not reduce the planet sensitivity (Ingrosso et al. 2009).

4. Can Gravitational Microlensing Detect Exoplanets in the SMC?

The upcoming LSST, as we show below, has the potential to observe 20–30 microlensing events in the SMC annually. However, the microlensing experiment would require significant changes to the default observing strategy to detect and characterize exoplanets in the SMC. The telescope will have a field of view of 9.6 deg² (which is sufficient to cover the central regions of the SMC with only a single LSST field) and will be able to detect objects as faint as $r = 24.7$ (AB magnitudes) in a single-visit image (see LSST Science Book; LSST Science Collaboration 2009). The survey is expected to last 10 years.

To estimate the number of sources that could be monitored by the LSST, we generated theoretical isochrones (see Section 2.3). The LSST is expected to register sources brighter than $r = 24.7$ (absolute magnitude of 5.8), i.e., in the mass range $[0.72, 0.93] M_\odot$ (old population) and $[0.78, 3.76] M_\odot$ (young population). Such stars comprise 7.2% of all stars in the SMC. This fraction is slightly smaller in $g$ and $i$ bands (given limiting magnitudes of $g = 25.0$ and $i = 24.0$; LSST Science Collaboration 2009). The expected observed event rate is simply the product of the mean event rate $\Gamma$ and the number of observable sources. It ranges from 20 to 26 per year, for “slow” and “fast” models, respectively.

The average number of epochs (~1000 over 10 years in all filters) in LSST fields is not sufficient to detect ongoing microlensing events and planetary anomalies. However, some fields are planned to be observed with a much higher cadence. We propose that one such high-cadence field should cover the central regions of the SMC. We also propose to observe this field, ideally, in single filter ($r$) each night, which is sufficient to trigger dense follow-up observations. However, such strategy requires an efficient system of real-time detections (Udalski et al. 1994) and rapid-response follow-up telescopes. High-magnification events, which are very sensitive to planets (Griest & Safizadeh 1998), can be followed up with smaller telescopes. The number of magnified events at any moment of time is small enough to warrant relatively small telescope-time demand. High-cadence observations also make it possible to remove virtually all false positives, like dwarf novae or background supernovae.

Another possible strategy is to observe the SMC field every 1–2 hr, which is sufficient to cover short-timescale planetary anomalies. Such an approach is adopted by current microlensing surveys of the Galactic bulge and allows discovering and characterizing planetary anomalies without the need of targeted follow-up observations. If neither of the above proposed strategies is adopted, a significantly smaller number of SMC events would be discovered. We estimate that over 80% of the SMC events could be detected in real-time (meaning that at least three consecutive data points deviate $3\sigma$ above the baseline before an event peaks) for a 1 day survey cadence. This number drops dramatically for lower cadence, for example, less than 30% of events could be detected in real-time if observations are conducted every 20 days.

How many planetary events are expected? Shvartzvald et al. (2016) conducted a “second generation” microlensing survey for extrasolar planets toward the Galactic bulge based on observations from OGLE, MOA, and WISE. They found that
over 12% of analyzed events showed deviations from single-lens microlensing, and in about one-third of those the anomaly was likely caused by a planet. Most probably, LSST observations of the SMC will not be able to achieve a 4% success rate, unless high-cadence follow-up is conducted. Shvartzvald et al. (2016) used nearly continuous observations of the Galactic bulge, while the SMC can be observed at most ~7 hr each night (above airmass 1.6). On the other hand, microlensing events in the SMC are on average three times longer than events observed toward the Galactic bulge, making the planetary deviations also longer.

If we assume that 1%–2% of SMC events have planetary anomalies (and take into account that the SMC can be observed during ~2/3 of a year), then the expected rate of planet detections is 0.1–0.5 yr^{-1}. A few extragalactic planets should be detected over the course of the LSST (or similar) survey. Besides detecting the microlensing events, high-cadence observations of the SMC can provide the opportunity to study the stellar variability on all timescales, stellar populations, star formation and chemical abundance history of the SMC (Szkody et al. 2011), or detect planetary transit candidates (Jacklin et al. 2015; Lund et al. 2015). We note that the SMC is better target for microlensing survey than the LMC because the former is elongated along the line of sight. The two galaxies do not differ much as transit survey targets.

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References

Alcock, C., Akerlof, C. W., Allsman, R. A., et al. 1993, Natur, 365, 621
Anglada-Escudé, G., Amado, P. J., Barnes, J., et al. 2016, Natur, 536, 437
Aubourg, E., Barentzen, P., Brethun, S., et al. 1993, Natur, 365, 623
Baltz, E. A., & Gondolo, P. 2001, ApJ, 559, 41
Batista, V., Gould, A., Dieters, S., et al. 2011, A&A, 529, A102
Bekki, K., & Chiba, M. 2009, PASA, 26, 48
Calchi Novati, S., Mirzoyan, S., Jetzer, P., & Scarpetta, G. 2013, MNRAS, 435, 1582
Calchi Novati, S., Paulin-Henriksson, S., An, J., et al. 2005, A&A, 443, 911
Cassan, A., Kubas, D., Beaulieu, J.-P., et al. 2012, Natur, 481, 167
Clanton, C., & Gould, B. S. 2014, ApJ, 791, 90
Corone, G., de Ritis, R., Dominik, M., & Marino, A. A. 2000, A&A, 357, 816
de Jong, J. T. A., Widrow, L. M., Cseresnjes, F., et al. 2006, A&A, 446, 855
Deb, S. 2017, arXiv:1707.03130
Dempster, A. P., Laird, N. M., & Rubin, D. B. 1977, Journal of the Royal Statistical Society, Series B, 39, 1
Dong, S., Udalski, A., Gould, A., et al. 2007, ApJ, 664, 862
Evans, C. J., & Howarth, I. D. 2008, MNRAS, 386, 826
Gould, A. 2000, ApJ, 535, 928
Gould, A., & Loeb, A. 1992, ApJ, 396, 104
Graff, D. S., & Gardiner, L. T. 1999, MNRAS, 307, 577
Griest, K., & Safizadeh, N. 1998, ApJ, 500, 37
Harris, J., & Zaritsky, D. 2006, AJ, 131, 2514
Haschke, R., Grebel, E. K., & Duffau, S. 2011, AJ, 141, 158
Howard, A. W., Marcy, G. W., Bryson, S. T., et al. 2012, ApJS, 201, 15
Ingrosso, G., Novati, S. C., de Paolis, F., et al. 2009, MNRAS, 399, 219
Jacklin, S., Lund, M. B., Pepper, J., & Stassun, K. G. 2015, AJ, 150, 34
Jarczyńska-Dobrzeniecka, A. M., Skowron, D. M., Mróz, P., et al. 2016, AcA, 66, 149
Jarczyńska-Dobrzeniecka, A. M., Skowron, D. M., Mróz, P., et al. 2017, AcA, 67, 1
Kaliliavali, N., van der Marel, R. P., Besla, G., Anderson, J., & Alcock, C. 2013, ApJ, 764, 161
Kiraga, M., & Paczynski, B. 1994, ApJL, 430, L101
Kroupa, P. 2001, MNRAS, 322, 231
LSST Science Collaboration 2009, arXiv:0912.0201
Lund, M. B., Pepper, J., & Stassun, K. G. 2015, AJ, 149, 16
Mao, S., & Paczynski, B. 1991, ApJ, 374, L37
Marigo, P., Girardi, L., Bressan, A., et al. 2017, ApJ, 835, 77
Mayor, M., Marmier, M., Lovis, C., et al. 2011, arXiv:1109.2497
Mayor, M., & Queloz, D. 1995, Natur, 378, 355
Mróz, P., Udalski, A., Skowron, J., et al. 2017, Natur, 548, 183
Muraveva, T., Subramanian, S., Clementini, G., et al. 2018, MNRAS, 473, 3131
Paczynski, B. 1986, ApJ, 304, 1
Palanque-Delabrouille, N., Afonso, C., Albert, J. N., et al. 1998, A&A, 332, 1
Penny, M. T., Henderson, C. B., & Clanton, C. 2016, ApJ, 830, 150
Ripepi, V., Cioni, M.-R. L., Moretti, M. I., et al. 2017, MNRAS, 472, 808
Sahu, K. C. 1994, Natur, 370, 275
Sahu, K. C., & Sahu, M. S. 1998, ApJL, 508, L147
Scowcroft, V., Freedman, W. L., Madore, B. F., et al. 2016, ApJ, 816, 49
Shvartzvald, Y., Maoz, D., Udalski, A., et al. 2016, MNRAS, 457, 4089
Soszyński, I., Udalski, A., Szymański, M. K., et al. 2015, AcA, 65, 297
Soszyński, I., Udalski, A., Szymański, M. K., et al. 2016, AcA, 66, 131
Stanimirović, S., Staveley-Smith, L., & Jones, P. A. 2004, ApJ, 604, 176
Szkody, P., Long, K. S., DiStefano, R., et al. 2011, Science White Paper for LSST Deep-Drilling Field Observations High Cadence Observations of the Magellanic Clouds and Select Galactic Cluster Fields (Tucson, AZ: LSST)
Tisserand, P., Le Guillou, L., Afonso, C., et al. 2007, A&A, 469, 387
Udalski, A., Szymański, M., Kaluzny, J., et al. 1994, AcA, 43, 289
Udalski, A., Szymański, M., Kaluzny, J., et al. 1993, A&A, 28, 227
Udalski, A., Szymański, M. K., & Szymański, G. 2015, AcA, 65, 1
van der Marel, R. P., Kaliliavali, N., & Besla, G. 2009, in IAU Symp. 256, The Magellanic System: Stars, Gas, and Galaxies, ed. J. M. Oliveira, S. Kozłowski, J. Skowron for reading the manuscript.

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