VVV Survey Microlensing: The Galactic Longitude Dependence

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Abstract

We completed the search for microlensing events in the zero latitude area of the Galactic bulge using the VVV Survey near-infrared (near-IR) data obtained between 2010 and 2015. We have now a total sample of \( N = 630 \) events. Using the near-IR color–magnitude diagram we selected the red clump (RC) sources to analyze the longitude dependence of microlensing across the central region of the Galactic plane. The events show a homogeneous distribution, smoothly increasing in numbers toward the Galactic center, as predicted by different models. We find a slight asymmetry, with a larger number of events toward negative longitudes than positive longitudes. This asymmetry is seen both in the complete sample and the subsample of RC giant sources, and it is possibly related with the inclination of the bar along the line of sight. The timescale distribution is fairly symmetric with a peak in \( 17.4 \pm 1.0 \) days for the complete sample \(( N = 630 \) events), and \( 20.7 \pm 1.0 \) days for the RC stars \(( N = 291 \) events), in agreement with previous results.

Key words: Galaxy: bulge – Galaxy: structure – gravitational lensing: micro

1. Introduction

The largest surveys dedicated to detect bulge microlensing events so far, such as the Massive Astrophysical Compact Halo Objects (MACHO; Alcock et al. 1993), the Optical Gravitational Lensing Experiment (OGLE; Udalski et al. 1993), the Microlensing Observations in Astrophysics (MOA; Bond et al. 2001), the Expérience pour la Recherche d’Objets Sombres (EROS; Aubourg et al. 1993), the Disk Unseen Objects (Alard et al. 1995), the Wise Observatory (Shvartzvald & Maoz 2012), and, more recently, the Korean Microlensing Telescope Network (Kim et al. 2010, 2017), have detected tens of thousands of events toward the Galactic bulge. However, the central Galactic plane (the low-latitude regions with \( |b| < 2^\circ \) surrounding the Galactic center) has not been studied because of the extremely high differential reddening and source crowding. In addition to being an unexplored area, it is an interesting area to study because the number of microlensing events is expected to increase toward the central Galactic plane region (Gould 1995; Wyzykowski et al. 2015; Shvartzvald et al. 2017). Moreover, the complete analysis of microlensing events at low latitudes and longitudes is very useful for optimizing the observational campaign for the Wide Field Infrared Survey Telescope (WFIRST; Green et al. 2012; Spergel et al. 2015).

With the new era of near-infrared (near-IR) surveys, such as the UKIRT microlensing survey (Shvartzvald et al. 2017, 2018) and the VISTA Variables in the Via Láctea Survey (VVV; Minniti et al. 2010), we are now able to penetrate the gas and dust to study the central Galactic plane in detail. In this framework we completed the search in the 14 VVV tiles located in the bulge centered at \( b = 0^\circ \). The proof of concept and initial results for the innermost three tiles (b332, b333, b334) were published in Navarro et al. (2017). We found 182 microlensing events, with an excess in the number of events in the central tile b333 in comparison with the other two tiles, and a relatively large number of long-timescale events (with \( t_\circ > 100 \) days). In this report we extend the area coverage, based on the 5 years long campaign of the VVV survey near-IR observations, and we present the spatial and timescale distribution analysis based on the final sample of microlensing events that is 3.5 times larger.

In Section 2 the data used to perform the search and the method is presented. In Section 3 we describe the analysis of the color–magnitude diagrams (CMDs), and in Section 4 we discuss the spatial distribution of the sample. The timescale analysis is discussed in Section 5. Finally, our conclusions are presented in Section 6.

2. Observations and Method

We use the data from the VVV (Minniti et al. 2010); that is, a near-IR variability survey that scans the Milky Way Bulge and an adjacent section of the mid-plane using the Visible and Infrared Survey Telescope for Astronomy (VISTA), a 4 m telescope located at ESO’s Cerro Paranal Observatory in Chile. The point spread function (PSF) photometry was carried out with DAOPHOT following the procedures described in detail by Contreras-Ramos et al. (2017). The total area analyzed here comprises 14 VVV tiles in the bulge (from b327 to b340) covering the region within \(-10^\circ.00 \leq l \leq 10^\circ.44\) and \(-0^\circ.46 \leq b \leq 0^\circ.65\). These data included from 73 (b340) to 104 epochs (b333) spanning six seasons (2010–2015) of observations. These multi-epoch magnitudes in the K-band comprise a total of about \( 63 \times 10^6 \) light curves for individual point sources.

The microlensing event selection follows the same procedure explained in Navarro et al. (2017), and M. G. Navarro et al. (2018, in preparation). Briefly, we fitted the standard microlensing model that assumes that the source and the lens are point-like objects (Refsdal 1964). The final sample contains 630 microlensing events, 182 of which were previously published in Navarro et al. (2017). Table 1 lists the Galactic coordinates of each tile, along with the number of total light curves analyzed, the number of events found, and the corresponding numbers of red clump (RC) events. A small
number of duplicate events found in overlap regions ($N = 36$) is already accounted for in this total sample.

3. Characterization of the Microlensing Events

For the microlensing analysis, it is usually better to restrict the sample to the RC giant stars. These are evolved low-mass stars that are burning helium in their cores and are located in a narrow band (Horizontal Branch) of the CMD, hence they act as good distance indicators. In optical microlensing experiments the use of RC stars is preferred because of three main reasons (Popowski et al. 2005; Sumi et al. 2005):

1. the probability for the source to be located in the bulge is higher,
2. they are bright and red, so that the photometric completeness is generally higher in the reddened bulge regions, and
3. they are bright enough that the blending effect might be negligible and, therefore, the parameters obtained from the light curve are more reliable.

The same applies to the near-IR VVV data. To identify better the RC in the CMD of areas where the extinction is extremely high and also variable such as this case, it is more advantageous to use the reddening corrected Wesenheit magnitude, according to the reddening law proposed by Alonso-García et al. (2017), defined as

$$W_k = K_s - 0.428(J - K_s),$$

Figure 1 shows the $W_k$ versus $J - K_s$ CMD of the area studied in this report plotted as a density map along with the sources of the microlensing events.

Table 1

| Tile   | $(l, b)$   | $N_{\text{raw}}$ | $N_{\text{events}}$ | $N_{\text{RC events}}$ |
|--------|------------|------------------|---------------------|------------------------|
| b327   | 350.737, 0.140 | 4041549 | 19 | 10 |
| b328   | 352.196, 0.140 | 3810368 | 19 | 7 |
| b329   | 353.655, 0.140 | 4246204 | 34 | 17 |
| b330   | 355.114, 0.140 | 4475365 | 60 | 26 |
| b331   | 356.572, 0.140 | 4533337 | 55 | 25 |
| b332   | 358.031, 0.140 | 4644686 | 71 | 32 |
| b333   | 359.409, 0.140 | 5147969 | 119 | 45 |
| b334   | 0.949, 0.140 | 4840898 | 75 | 36 |
| b335   | 2.407, 0.140 | 4586590 | 56 | 35 |
| b336   | 3.866, 0.140 | 4709192 | 42 | 24 |
| b337   | 5.325, 0.140 | 4490887 | 33 | 17 |
| b338   | 6.783, 0.140 | 4588556 | 21 | 8 |
| b339   | 8.242, 0.140 | 4419377 | 13 | 4 |
| b340   | 9.701, 0.140 | 4245168 | 13 | 5 |
| Total  |             | 62760625 | 630 | 291 |

Figure 1. Near-IR $W_K$ vs. $J - K_s$ CMD for the 14 VVV tiles (from b327 to b340). This is a logarithmic color-coded Hess diagram representation of the 63 million individual sources. The black circles indicate the sources of the sample microlensing events, and the white circles are the sources located in the RC. The $W_K$ histogram of the microlensing events sample is shown in the right panel of the figure.

From the near-IR CMD it is clear that the RC stars are well above the VVV incompleteness limit that sets at about $K_s > 17.5$ mag, except for the reddest sources with $J - K_s > 5.0$ mag that are affected by the high extinction present in the inner bulge and may be missing from our search, thus we estimate the color using the $J$ mag detection limit of the CMD. Also, the bluer stars with $J - K_s < 1.5$ mag are deemed to be foreground disk sources. We find a total of $N = 16$ disk sources, very few ($\sim 3\%$) in comparison with the total number of events. The total number of measured stars per tile are listed in Table 1, along with the total number of microlensing events and RC events.

Using the extinction ratios for this region from Alonso-García et al. (2017), we adopt the mean intrinsic magnitude and color of the RC to be $M_{K_s} = -1.606 \pm 0.009$, and $(J - K_s)_{0} = 0.66 \pm 0.01$ mag from Ruiz-Dern et al. (2018). The blue color cut made here to select RC giants at $J - K_s > 2.0$ yields extinction and reddening values of $E(J - K_s) > 1.34$, and $A_{K_s} > 0.57$ mag, respectively. The reddest RC sources detected in both the $J$- and $K_s$-bands have $J - K_s > 1.7$ implying $E(J - K_s) > 5.34$, and $A_{K_s} > 2.28$. Some of the most reddened sources are not detected in the $J$-band at all, but in analyzing the $H$-band magnitude of the events we note that the reddest RC sources detected in both the $H$- and $K_s$-bands have $H - K_s > 2.3$ yielding $A_{K_s} = 2.36$. Assuming $A_{K_s}/A_V \approx 0.11$ (Schlafly & Finkbeiner 2011), the reddest sources of microlensing events observed here would have optical extinctions up to $A_V \sim 21$ mag. Such microlensing events are beyond detection for current optical surveys, suggesting that our sample can include events with sources in the far disk. Only a microlensing search with WFIRST would be capable of improving upon the results from current the near-IR ground-based surveys.

4. Spatial Distribution

The spatial distribution of the complete sample is shown in Figure 2, along with the distribution of events discovered by the OGLE and MOA optical surveys between years 2010 and 2015 (Sumi et al. 2013; Wyzykowski et al. 2015). This figure underscores the importance of the VVV survey that completes
the microlensing census at low latitudes, where the optical surveys are blind because of the high extinction.

The longitude distribution of the total number of events is shown in Figure 3. This distribution clearly shows that the number of events increases toward the Galactic center and confirms the excess of lenses in the Galactic center found in Navarro et al. (2017). This is not only due to the higher stellar density, but it is a real increase in the microlensing rate. The number of light curves analyzed increases only by about 20% from the edges ($|l| = 10^\circ$) to the Galactic center at $l = 0^\circ$, while in comparison the total number of events increases by almost a factor of five (compare Table 1).

The distribution is also not symmetric about the Galactic minor axis, as the negative Galactic longitudes exhibit a higher number density of events (~60%) than the positive ones. Additionally, there are some inhomogeneities: regions of overdensity of events, as well as regions with fewer events. A visual inspection reveals that the overdensities and underdensities seem to be correlated with reddening, in the sense that the more reddened the field, the smaller the number of events. If this is the case, the real number of events in the central-most regions that are generally more reddened (like the Galactic center tile b333) may be larger than observed.

There are two main competing effects to take into account. We expect a higher number of events toward the center due to the density profile of the galaxy that is known to increase toward the center. Contrary to this, the extinction is higher toward the central fields, therefore the number of observed events is expected to become more incomplete as we approach the Galactic center due to the heavy extinction.

We use the number of events normalized to the total number of stars per tile. Taking into account the total sample, this fraction is $N_{\text{total}} = 1.0 \times 10^{-5}$. This is not constant across the plane, as the normalized number of events per number of stars clearly increases toward the Galactic center.

The use of RC giants should minimize the incompleteness; we examine the RC events, that is the 46% of the sample, to strengthen the results obtained from the total sample. They are as follows.

1. There is a smooth increase in the RC event numbers toward the Galactic center. This was predicted by all of the available models.

Figure 2. Spatial distribution of the new microlensing events (magenta crosses) around the Galactic center with the events published by OGLE (blue crosses) and MOA (cyan crosses) between 2010 and 2015. The duplicate events in the overlapping VVV areas have been accounted for.

Figure 3. Top panel: histogram of Galactic longitude of the $6.3 \times 10^6$ stars detected in the area within the 14 VVV tiles analyzed. Second panel: histogram of Galactic longitude of the total events detected in this research. Third panel: histogram of Galactic longitude of the events located in the RC. The colored lines are the best Gaussian fit for each case, with the indicated means and sigmas. Bottom panel: distribution of the relative number of microlensing events ($N_{\text{events}}/N_{\text{stars}}$) as function of Galactic longitude. The upper and lower histograms show the total number of events and RC events, respectively.
2. The central number of RC events at $l = 0^\circ$ is $\sim$5 times the number at $l = 10^\circ$. This effect is more pronounced considering the normalized number of RC events $N_{\text{RC,events}}/N_{\text{stars}}$, where a stronger increase is seen, with the number at the center being $\sim$8 times larger than that at $l = 10^\circ$. The different existing models make different predictions, and this observed number is important to quantitatively fine-tune future models.

3. The RC event distribution is non axisymmetric, with an excess of events at negative longitudes. Excluding the five central tiles with $-3^\circ < l < 3^\circ$, there are $\sim$20% more RC events in the tiles at negative longitudes with $-10^\circ < l < -3^\circ$ ($N_{\text{RC}} = 90$ events) than in the tiles at positive longitudes with $3^\circ < l < 10^\circ$ ($N_{\text{RC}} = 71$ events). This result was not predicted by the existing models. These results are more evident considering the sampling efficiency corrections (that yield $\sim$32%).

This asymmetry in the number of microlensing events at zero latitude can be explained by the inclination of the bar. At negative longitudes we not only have a longer line of sight before hitting the main bulge sources that are located at the opposite side of the bar, but also the length of the optical path through the bar itself is longer than at positive latitudes. The first effect causes more bulge–disk events, while the latter produces more bulge–bulge events. Consequently, the probability for detecting microlensing events is larger toward negative longitudes, as observed. However, this detection is of low statistical significance ($\sim 2\sigma$).

Interestingly, the optical microlensing events that map higher Galactic latitudes have not observed such a pronounced asymmetry. This may be due to a strong dependence of the effect of the bar with latitude. The VVV microlensing work allows us for the first time to probe these spatial dependencies all the way to the Galactic plane and center, in spite of the strong obscuration in these fields.

5. Timescale Distribution

The only important physical parameter obtained from the standard microlensing model fitting procedure is the Einstein radius crossing time ($t_\text{E}$), also called the microlensing timescale. This timescale is related to the mass of the lens but also depends on the relative distances (distance between the observer and the lens $D_L$ and between the observer and the source $D_S$), and the relative transverse velocity (Paczyński 1986). Thus, although the Einstein radius crossing time is extremely degenerate, the timescale distribution of the sample gives an indication of the masses and velocities of the lenses. Therefore, the timescale distribution depends on the mass function and the velocity dispersion of the lens population.

The observed timescale distribution is affected by the detection efficiency, which is discussed in detail by M. G. Navarro et al. (2018, in preparation). Briefly, the sampling efficiency is cadence and timescale dependent (Mróz et al. 2017), so therefore was evaluated using Monte Carlo simulations of 10,000 events for each fixed representative timescales (1, 3, 5, 10, 20, 40, 60, 80, 100, 150, and 200 days). This procedure was computed for each VVV tile.

For the photometric efficiencies, we used the extensive PSF photometric simulations made for the VVV survey by Valenti et al. (2016) and Contreras-Ramos et al. (2018). For example, comparing the sample of low-amplitude RR Lyrae population with the OGLE catalog yields a completeness of 90% at $K_s \sim 15$ mag. The observed timescale distribution was corrected accordingly, also excluding the first VVV observation season (2010) because of the small number of observations.

The efficiency-corrected timescale distribution (for the model including blending effects) obtained in this work is shown in Figure 4, along with the models of Wegg et al. (2016). The mean timescale is $17.4 \pm 1.0$ days for the complete sample, and $20.7 \pm 1.0$ days for the RC sample.

Both distributions are in good agreement, and suggest that the typical lenses are lower main-sequence stars and brown dwarfs. For the model without blending the distribution is similar with values slightly lower toward short timescale events and a mean timescale of $13.9 \pm 1.0$ and $16.5 \pm 1.0$ days for the complete and the RC samples, respectively.

Previous studies at higher latitudes, like OGLE, obtained $\langle t_{\text{E}} \rangle \sim 32$ days and $\langle t_{\text{E}} \rangle \sim 28$ days for uncorrected and efficiency-corrected cases, respectively (Sumi et al. 2005). Likewise, EROS obtained $\langle t_{\text{E}} \rangle \sim 33$ days (Afonso et al. 2003). The distributions obtained by MOA acquired (Sumi et al. 2013) $\langle t_{\text{E}} \rangle \sim 24$ days ($\langle t_{\text{E}} \rangle \sim 19$ days) for the complete sample (RC sources) and OGLE (Wyrzykowski et al. 2015) inferred $\langle t_{\text{E}} \rangle \sim 22, 20, 24$ days for positive, central, and negative longitudes respectively. Some of the studies just mentioned (Sumi et al. 2013; Wyrzykowski et al. 2015) show changes in the timescale distribution with longitude and latitude, specifically a decrease in timescale toward the central area of the Galaxy. Therefore, as this is the first time that this area is analyzed, a straight comparison with previous results cannot be done. Our Galactic plane fields have mean timescales shorter than the previous studies, as expected from the model predictions of Wood & Mao (2005) and Awiphan et al. (2016), where the trend is also evident.

![Figure 4. Distribution of the efficiency-corrected timescales with blending excluding the first year of VVV observations, for the complete sample (in blue), and the RC events subsample (in red), along with the error bars for each bin. Dot lines show the best fit model of each distribution. The green line shows the lognormal distributions of the model proposed by Wegg et al. (2016), arbitrarily normalized to the peak. Poisson error bars for each bin are presented.](image-url)
Thus, we compare our results with models, such as the one proposed by Wegg et al. (2016). The model is in correct agreement with our results in the central part, where we found the higher number of events, and in the short timescale tail. However, we observe a small excess of long-timescale events ($t_L > 100$ days) that needs to be confirmed because it is still within the errors.

6. Conclusions

We have detected 630 microlensing events within an area of 20.68 deg$^2$ around the Galactic center ($-10°00' \leq l \leq 10°44'$ and $-0°46' \leq b \leq 0°65'$) using the deep near-IR VVV Survey photometry.

This is the first time a longitude analysis of the microlensing event population has been performed across the central Galactic plane at $b = 0°$. We found a decrease in the total number of events with increasing Galactic longitude. That was predicted by the models, partly due to the density of stars that increases toward the Galactic center. We also found a higher concentration of events toward negative longitudes. This trend is observed both for the full sample and for the RC subsample. This can be explained by the inclination of the bar, as the line of sight toward the negative latitudes is longer, increasing the probability of producing microlensing events.

In order to strengthen the results, it is better to restrict the sample to RC stars for three main reasons: higher probability to be located at the bulge, better completeness, and negligible blending effect.

The efficiency-corrected timescale distribution also is analyzed for the entire sample and RC subsample. The distribution shows a shorter mean timescale than that obtained in previous studies by surveys such as OGLE, MOA, MACHO, and EROS. This result is in agreement with previous observational studies that show a decrease in the mean timescale all the way to the center of the Galaxy.

The comparison of our distribution with the existing models shows a correct agreement in spite of a slight inconsistency at the long-timescale tail; this requires confirmation using larger samples.

The VVV Survey is a powerful tool to detect microlensing events and to study this population at low latitudes where the optical observations are limited. This can be useful to plan the observations of the WFIRST microlensing survey (Green et al. 2012; Spergel et al. 2015). When considering only the total number of lensing events, we suggest that a WFIRST survey across the Galactic plane covering the whole bulge would be most profitable for microlensing science, especially using a K-band filter as suggested by Stauffer et al. (2018).

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