Measurements of streaming motions of the Galactic Bar with Red Clump Giants

T. Sumi, L. Eyer and P. R. Woźniak

1,2 Princeton University Observatory, Princeton, NJ 08544-1001, USA; e-mail: sumi@astro.princeton.edu, leyer@astro.princeton.edu
3 Los Alamos National Laboratory, MS-D436, Los Alamos, NM 87545; e-mail: wozniak@lanl.gov

Accepted Received in original form

ABSTRACT
We report a measurement of the streaming motion of the stars in the Galactic bar with the Red Clump Giants (RCGs) using the data of the Optical Gravitational Lensing Experiment II (OGLE-II). We measure the proper motion of 46,961 stars and divide RCGs into bright and faint sub-samples which on average will be closer to the near and far side of the bar, respectively. We find that the far-side RCGs (4,979 stars) have a proper motion of $\Delta < \mu > \sim 1.5 \pm 0.11$ mas yr$^{-1}$ toward the negative $l$ relative to the near-side RCGs (3,610 stars). This result can be explained by stars in the bar rotating around the Galactic center in the same direction as the Sun with $v_b \sim 100$ km s$^{-1}$. In the Disc Star (DS) and Red Giant (RG) samples, we do not find significant difference between bright and faint sub-samples. For those samples $\Delta < \mu > \sim 0.3 \pm 0.14$ mas yr$^{-1}$ and $\sim 0.03 \pm 0.14$ mas yr$^{-1}$, respectively. It is likely that the average proper motion of RG stars is the same as that of the Galactic center. The proper motion of DSs with respect to RGs is $\sim 3.3$ mas yr$^{-1}$ toward positive $l$. This value is consistent with the expectations for a flat rotation curve and Solar motion with respect to local standard of rest. RGs have proper motion approximately equal to the average of bright and faint RCGs, which implies that they are on average near the center of the bar. This pilot project demonstrates that OGLE-II data may be used to study streaming motions of stars in the Galactic bar. We intend to extend this work to all 49 OGLE-II fields in the Galactic bulge region.

Key words: Galaxy:bulge – Galaxy:center – Galaxy:kinematics and dynamics–Galaxy:structure

1 INTRODUCTION
Several groups have carried out gravitational microlensing observations toward dense stellar fields, such as the Magellanic clouds, the Galactic center and disc. Until now, hundreds of events have been found (EROS: Aubourg et al. 1993; OGLE: Udalski et al. 1993, 1994, 2000; Woźniak et al. 2001; MACHO: Alcock et al. 1997, 2000a,b; MOA: Bond et al. 2001, 2002), and thousands are expected in the upcoming years by MOA 2, OGLE-III 3 and other collaborations.

It is well known that the gravitational microlensing survey data is well suited for numerous other scientific projects (see Paczynski 1996, Gould 1996). The studies of the Galactic structure certainly benefit from this type of data. The microlensing optical depth probes the mass density of compact objects along the line of sight and the event time-scale distribution is related to the mass function and kinematics of the lensing objects. Observed high optical depth may be explained by the presence of the bar (Udalski et al. 1994, Alcock et al. 1997, 2000a, Sumi et al. 2002). There is substantial evidence that the Galaxy has a bar at its center (de Vaucouleurs 1964, Blitz & Spergel 1991, Stanek et al. 1994, 1997, Kiraga & Paczynski 1994, Infner et al. 2000). However, the parameters of the bar, e.g., its mass, size, and the motion of stars within it, still remain poorly constrained.

Stanek et al. (1997) used the Red Clump Giants (RCGs) to constrain the axial ratios and orientation of the Galactic bar. These stars are the equivalent of the horizontal branch stars for a metal-rich population, i.e., relatively low-mass core helium burning stars. RCGs in the Galactic bulge occupy a distinct region in the colour magnitude diagram (Stanek et al. 2000 and references therein). The intrinsic width of the luminosity distribution of RCGs in the Galactic bulge is small, about 0.2 mag (Stanek et al. 1997, Paczynski & Stanek 1998). Their observed peak and width of the lumi-
nosity function are related to the distance and radial depth of the bar.

Furthermore, Mao & Paczynski (2002) suggested that the proper motion measurements of RCGs in the Galactic center are useful in constraining the Galactic bar parameters. By considering a sub-sample of bright RCGs, one should be able to isolate to a sufficient degree the stars that are on average closer to the near side of the bar. Similarly, the stars in a faint sub-sample would be more on the far side of the bar. If there is a tangential streaming motion of 100 km s$^{-1}$ in the bulge/bar, there should be a detectable difference of 1.6 mas yr$^{-1}$ in the average proper motion between the bright and faint RCG sub-samples. Measurements of this difference provide constraints on the models of the Galactic bar.

To test the feasibility of the method, in this paper we analyze stellar proper motions in one of the fields observed by the Optical Gravitational Experiment II (OGLE-II; Udalski et al. 2001). In §3 we describe the data. We present the analysis method in §4 and results in §5. Discussion and conclusion are given in §6.

2 DATA

We use the data collected during the second phase of the OGLE experiment, between 1997 and 2000. All observations were made with the 1.3-m Warsaw telescope located at the Las Campanas Observatory, Chile, which is operated by the Carnegie Institution of Washington. The "first generation" camera has a SITe 2048 × 2048 pixel CCD detector with pixel size of 24 μm resulting in 0.417 arcsec/pixel scale. Images of the Galactic bulge were taken in drift-scan mode at "medium" readout speed with the gain 7.1 e$^{-}$/ADU and readout noise of 6.3 e$^{-}$. A single 2048 × 8192 pixel frame covers an area of 0.24 × 0.95 deg$^2$. Saturation level is about 55,000 ADU. Details of the instrumentation setup can be seen in Udalski, Kubiak & Szymański [1991].

In this paper we use 266 I-band frames of the BUL_SC1 field centered at ($\alpha$, $\delta$)$_{2000} = (18^h02^m32.5, -29^\circ57'41'')$. The time baseline is almost 4 years. There are gaps between the observing seasons when the Galactic bulge cannot be observed from Las Campanas, each about 3 months long. The median seeing is $\sim$ 1.3$''$. We use the $VI$ photometric maps of standard OGLE template (Udalski et al. 2002) as the astrometric and photometric references.

Only about 70% of the area of the BUL_SC1 field overlaps with the extinction map made by Stanek (1996) and is used in the analysis. This ensures that we can accurately deredden stellar magnitudes.

3 ANALYSIS

The standard OGLE template serves as the fixed astrometric reference in our analysis. In the case of BUL_SC1 field, the frame adopted as the OGLE template was taken at JD = 2450561.715. In order to treat properly spatial PSF variations and frame distortions the field is divided into 256 subframes before processing. Subframes are 512 × 128 pixels with 14 pixel margin on each side to smooth out transitions between the local polynomial fits. The shape of the subframe reflects stronger y-axis (declination) gradients due to drift-scan mode of observation. The actual proper motion analysis includes only 180 subframes, that is 70% of the area of the BUL_SC1 field for which the accurate interstellar extinction data is available from Stanek (1996).

We compute the pixel positions of stars in each of the subframes using the DoPHOT package (Schechter, Mateo & Saha 1993). At the start of the processing for each exposure, the positions of stars in a single subframe are cross-referenced with those in the template and the overall frame shift is obtained. Using this crude shift we can identify the same region of the sky (corresponding to a given subframe of the template) throughout the entire sequence of frames. For each of the subframes, about $\sim$ 300 brightest ($I < 17$) stars categorized by DOPHOT as isolated are used to derive the local transformation between pixel coordinate systems of a given exposure and the template. The search radius in matching the stars between tempetle and other frames is 0.5 pixel. We use first order polynomial to fit the transformation. The resulting piece-wise transformation adequately converts pixel positions to the reference frame of the template. Typical residuals are at the level of 0.08 pixels.

An example of time dependence of the position for a star with the detectable proper motion is shown in Fig. 3. Also presented is the best fit model of proper motion ($\mu_\alpha$, $\mu_\delta$) with and without the differential refraction. The star’s coordinates in the sky at the time $t$ are given as follows:

$$\alpha = \alpha_0 + \mu_\alpha t + a \sin C \tan z,$$

$$\delta = \delta_0 + \mu_\delta t + a \cos C \tan z,$$

where $a$, $z$ and $C$ are the differential refraction coefficient, the zenith angle and the angle made by the Zenith, the star and the South Pole; $\alpha_0$ and $\delta_0$ are constants. The parameter $a$ is a function of the apparent star colour. Here we neglect the parallax effect due to the Earth motion because we are interested in stars at the distance of the Galactic center.

We computed $\alpha_0$, $\delta_0$, $\mu_\alpha$, $\mu_\delta$ and $a$ for all 46,961 stars used to transform coordinate systems (approximately the number of used subframes times the typical number of stars per subframe, 180 × 300). In cases when the star is measured in the overlap region of more than one subframe, the data set with the largest number of points is selected. Stars with the number of data points fewer than 20 are rejected. A sample of fitted proper motions is listed in Table 1. The complete list of all 46,961 stars is available in electric format via anonymous ftp from the server astro.princeton.edu, directory /sumi/propermotion/bul_sc1.pm.gz. The list contains star ID, number of data points, measured $\mu_\alpha$ and $\mu_\delta$ with their errors, $a$, standard deviation (Sdev) of data points in the fitting, equatorial coordinates, apparent I-band magnitude and $V - I$ colour, and extinction corrected magnitude $I_0$ and colour $(V - I)_0$ estimated using the extinction map of Stanek (1996). ID, coordinates, $I$ and $V - I$ for each object are identical with those in Udalski et al. 2002.

In Fig. 3, we present the $I$ and $V-I$ Colour Magnitude Diagram (CMD) of stars used in this analysis. We also show the correlation between the differential refraction coefficient $a$ and the apparent $V-I$ colour (uncorrected for extinction) for stars with $I < 16$. In Fig. 3, we plot the uncertainty in $\mu_i$. 

---

References:

Mao & Paczynski (2002)

Udalski et al. 2000

Schechter, Mateo & Saha (1993)

Stanek (1996)

Schechter, Mateo & Saha 1993

Saha 1993

DoPHOT package

Schechter, Mateo & Saha (1993)
Measurements of Streaming Motions of the Galactic Bar

Table 1. Sample of fitted parameters.

| ID   | N   | μα cos δ | σμα cos δ | μδ | σμδ | Sdev | α2000 | δ2000 | I | V − I | I0 | (V − I)0 |
|------|-----|----------|-----------|----|-----|------|-------|-------|--|-------|---|----------|
| 11933| 263 | 3.86     | 0.49      | 5.68| 0.49| 0.70 | 9.45  | -30.33 | 12.617| 1.878 | 11.638 | 1.241 |
| 11934| 230 | -3.18    | 0.52      | 4.45| 0.52| -10.40 | 9.37  | -30.33 | 12.747| 2.257 | 11.667 | 1.550 |
| 11936| 263 | 1.07     | 0.58      | 1.95| 0.58| 3.01 | 11.34 | 34.05  | 9.80  | 11.638 | 1.241 |
| 11937| 243 | -4.46    | 0.46      | -0.13| 0.45| 34.05 | 8.80  | -30.33 | 12.868| 4.805 | 11.790 | 4.092 |
| 11938| 263 | 1.19     | 0.51      | 3.11| 0.51| 20.69 | 11.34 | -30.33 | 12.254| 0.663 | 11.195 | -0.022 |
| 11939| 198 | -4.30    | 0.71      | 0.76| 0.70| 14.21 | 11.82 | -30.33 | 12.747| 2.257 | 11.667 | 1.550 |
| 11943| 261 | 1.84     | 0.54      | 3.73| 0.54| -11.53 | 10.50 | -30.33 | 13.220| 0.483 | 12.241 | -0.154 |
| 11945| 262 | 2.13     | 0.45      | 3.92| 0.45| 3.06 | 11.34 | 34.05  | 9.80  | 11.638 | 1.241 |
| 11948| 259 | 1.10     | 0.41      | 26.13| 0.41| 20.69 | 11.34 | -30.33 | 12.254| 0.663 | 11.195 | -0.022 |
| 11950| 266 | 0.28     | 0.53      | 2.26| 0.53| 4.35 | 10.33 | 18.0359 | 21479 | 12.254 | 0.663 | 11.195 |
| 11951| 245 | -1.10    | 0.41      | 0.02| 0.41| 26.13 | 7.83  | 18.0348 | 84     | 12.747 | 2.257 | 11.667 |
| 11952| 248 | 1.59     | 0.53      | -6.59| 0.53| -11.53 | 10.50 | -30.33 | 13.220| 0.483 | 12.241 | -0.154 |
| 11953| 244 | -8.37    | 1.42      | -2.66| 1.41| -3.02 | 26.65 | 18.0365 | 9234   | 13.072 | 4.608 | 12.129 |
| 11955| 265 | -0.56    | 0.37      | 0.06| 0.37| 26.13 | 7.83  | 18.0351 | 74968 | 12.247 | 3.679 | 11.145 |

Figure 1. Time variation of the position in α cos δ (upper) and δ (lower) of star ID=23679 (V-I=3.027). Solid line indicates a model fit of the proper motion (μα, μδ) = (3.8, -1.4) (mas yr⁻¹) with a differential refraction a = 10.4 mas (tan z)⁻¹, and dashed line represents the same line without the term of differential refraction.

Table 2. Mean of uncertainty in μ, < σμ > (mas yr⁻¹), as a function of I0 (mag). σμ is averaged over I0 ± 0.5.

| I0   | 10  | 11  | 12  | 13  | 14  | 15  | 16  |
|------|-----|-----|-----|-----|-----|-----|-----|
| < σμ > | 4.84 | 1.40 | 0.83 | 0.88 | 1.18 | 1.80 | 3.44 |

σμ, as a function of extinction corrected I-band magnitude I0, and we list the mean < σμ > in Table 2.

To check the measurements we cross-identified our stars with the list of high proper motion objects detected photometrically by Eyer & Woźniak (2001). Out of 74 stars in Eyer & Woźniak (2001), 53 are in the region used in the present analysis, and 52 were recovered. We plot the proper motions of those 52 stars as measured in both Eyer & Woźniak (2001) (μEW) and this work (μ). The very good correlation gives us certain confidence in our measurements.

Fig. 2 shows the histogram of μEW (thick solid line), μ of all 46,961 sample (dotted line), the sample detected with the confidence better than 3σ (dot-dashed line), better than 5σ (dashed line) and better than 10σ (thin solid line). We can

Figure 2. Upper: Colour magnitude diagram of the half of the analysed stars. Lower: Correlation between the differential refraction coefficient a and the apparent colour (uncorrected for extinction) for stars with I < 16.
Figure 3. Uncertainty in $\mu$ as a function of the extinction corrected I-band magnitude $I_0$.

Figure 4. Comparison of proper motions for 52 stars measured in both Eyer & Woźniak (2001) ($\mu_{EW}$) and this analysis ($\mu$).

see that our method is more effective in detecting proper motions than Eyer & Woźniak (2001).

4 RESULTS

For the purpose of proper motion analysis we identify three populations of stars: RCGs, Disc Stars (DSs) and Red Giants (RGs). Those occupy respectively the upper-right, upper-left and lower-right regions in Fig. 6, the extinction corrected CMD. Within each population we distinguish a bright and a faint sub-sample indicated by thick and thin boxes in the same figure. Those regions of the CMD are defined by the following formula:

13.5 < $I_0$ < 14.23 (bright RCGs),

14.39 < $I_0$ < 14.76 (faint RCGs),

0.84 < ($V - I$)$_0$ < 1.38 (both RCGs),

13.0 < $I_0$ < 15.0 (bright DSs),

15.0 < $I_0$ < 16.0 (faint DSs),

0.3 < ($V - I$)$_0$ < 0.7 (both DSs),

15.4 < $I_0$ < 15.9 (bright RGs),

16.0 < $I_0$ < 16.5 (faint RGs),

0.9 < ($V - I$)$_0$ < 1.5 (both RGs).

The CMD region for the RCGs was found to maximize the significance of the proper motion difference between bright and faint samples.
Figs. 6 and 7 summarize the main results. In Fig. 6 we show a histogram of \( \mu_\alpha \) (left panel) and \( \mu_\delta \) (right panel) for bright (thick line) and faint (dashed line) samples of all three stellar populations. Fig. 7 shows the contour map and the mean of the distribution in \( \mu_\alpha \) and \( \mu_\delta \) for bright (thick line and cross) and faint (thin line and cross) samples of RCGs, DSs and RGs. In this figure, the top-left corner is toward positive \( l \) and bottom-right corner is toward negative \( l \) direction. We also show the mean value of the relative proper motion \( < \mu > \) in equatorial and Galactic coordinates as well as the corresponding Root Mean Square (RMS) in equatorial coordinates for each of the samples in Table 3. We assumed that the error in \( \mu \) of each star is the RMS of the related distribution. This RMS is the combination of the intrinsic scatter in \( \mu \) and the astrometric uncertainty and therefore it provides a sensible upper limit for the error in \( < \mu > \). In measuring the mean value we rejected high proper motion objects with \( |\mu| > 20 \text{ mas yr}^{-1} \). Note that the mean values \( < \mu > \) of all sample are not exactly zero, as these are not identical to all stars used to align the frames. Stars with fewer than 20 data points and detected multiple times in the overlapping subframes were rejected. The differences are insignificant and we can safely ignore them.

Finally, we also show the mean positional shift of stars in each population as a function of time (JD) in Fig. 8. The plots of each samples, i.e., all (dot), bright (filled circle) and faint (open circle), are shifted vertically for clarity, because only the slope is important.

In Figs. 6, 7 and Table 3, differences in \( < \mu > \) between bright and faint samples of RCGs are clearly seen. The main component is along \( < \mu > \) and reaches \( \Delta < \mu > \sim 1.5 \text{ mas yr}^{-1} \). The accuracy in \( \Delta < \mu > \) is about \( \sigma \sim 0.11 \text{ mas yr}^{-1} \), therefore the significance of the difference is \( \sim 14\sigma \). In short, stars at the far side are moving toward negative Galactic latitude \( l \) relative to the stars at the near side. The magnitude and orientation of the proper motion of one group relative to the other can be explained by the rotation of stars in the bar in the same direction as the solar motion around the Galactic center. The result is consistent with \( \Delta < \mu > \sim 1.6 \text{ mas yr}^{-1} \) estimated by Mao 

\& Paczynski (2002) using the Kiraga 

\& Paczynski (1994)'s model with the tangential streaming motion of \( v_\ell \sim 100 \text{ km s}^{-1} \). Note that in this analysis the measured \( < \mu > \) is not absolute, but relative. Although the astrometric reference frame seems to be close to the one based on stars at the near side of the bar, in principle it is not associated with any pneumatically defined stellar population. On the other hand, the difference \( \Delta < \mu > \) between the two populations of RCGs is properly defined and reliable.

Both RG samples have same proper motion and values of \( < \mu > \) are about a mid between those of bright and faint RCGs. This can be explained by that RGs are on average at the center of the bar.

The disc stars seem to be moving toward positive \( l \) with \( < \mu > \sim 3.3 \text{ mas yr}^{-1} \) with respect to RGs, i.e., the Galactic center. This is roughly consistent with \( < \mu > \sim 3.2 \text{ mas yr}^{-1} \) estimated assuming that disc stars are on average on the \( \sim 1 \) kpc from the Sun and the flat rotation curve of \( v_\ell \sim 220 \text{ km s}^{-1} \). Here we also assumed that the Sun has an additional velocity of \( 19 \text{ km s}^{-1} \) toward \( (l, b) = (53^\circ, 25^\circ) \) relative to the Local Standard of Rest (LSR) (Binney 

\& Tremaine 1987), i.e., \((v_\odot, v_\odot) = (12 \text{ km s}^{-1}, 7 \text{ km s}^{-1})\). As for the disc stars, their distance may be estimated from their apparent brightness. They are typically at the main sequence turn-off point for an old population, so very crudely they have absolute magnitude \( M_I,0 \approx 4 \) or so. The bright DSs are at about \( I_0 = 14 \text{ mag} \), the faint are at about \( I_0 = 15.5 \text{ mag} \). So, their distance moduli are approximately 10 mag and 11.5 mag, which corresponds to the distance from us: 1 kpc and 2 kpc, respectively. For the faint DSs, slightly larger proper motion with respect to RGs is expected than the measured one. This difference might be due to the difference in rotation curve along the line of sight. The values \( < \mu_\odot > \sim 0.3 \) (bright DSs) or \(-0.05 \) (faint DSs) might be explained by the solar motion \((v_\odot, v_\odot)\) relative to LSR. A detailed analysis of these results is beyond the scope of this pilot study.

5 DISCUSSION AND CONCLUSION

We have measured the proper motion for 46,961 stars in the OGLE-II BULSC1 field covering Baade’s window. We dramatically increased the number of objects with large proper motions in this field compared to Eyer 

\& Wozniak (2001)
who detected 53 high proper motion objects in the same region of the Galactic bulge. We have estimated the difference in the proper motion between the bright (near-side) and the faint (far-side) samples of RCGs. We found that the far-side RCGs have a proper motion of $\Delta <\mu > \sim 1.5 \pm 0.011$ mas yr$^{-1}$ toward the negative $l$ relative to the near-side RCGs. The results fit the picture with stars in the bar rotating around the Galactic center in the same direction as the Sun. The value $\Delta <\mu > \sim 1.5$ mas yr$^{-1}$ is consistent with 1.6 mas yr$^{-1}$ estimated by Mao & Paczyński (2002) who assumed a streaming motion of the bar at $v_b \sim 100$ km s$^{-1}$. The presented method used with the OGLE-II data is sensitive to the relative streaming motion of stars in the Galactic bar down to about $\Delta <\mu > \sim 0.1$ mas yr$^{-1}$.

As discussed in the previous section, the measured proper motions of DS and RG samples seem consistent with the basic understanding of stellar motions in the Galaxy, and the Solar motion relative to LSR in particular. This consistency supports the reliability of our analysis.

The question of possible contamination by stars in the Galactic disc bears some discussion as we select the samples of RCGs using the CMD. Only nearby disc main-sequence stars, or evolved disc stars are expected to fall in the same CMD region as our RCG samples. The effect can be considered negligible because these stars are not very numerous (Stanek et al. 1994).

One should keep in mind that all measurements of $<\mu>$ presented here are not absolute, but relative to the astrometric reference frame which is not well known. This problem can be solved by using background quasars that would be detected in the near future using the OGLE-II variability catalog (Woźniak et al. 2002; Eyer 2003). The primary goal of this paper is to demonstrate that proper motions can be measured with very high precision using the OGLE-II data, sufficiently high to clearly detect the presence of a strong streaming motion (rotation) of stars in the Galactic bar. While the reference frame established by the large number of stars is not well defined with respect to the inertial frame of reference, the relative motions of groups of stars are well determined. A detailed analysis of these results is beyond the scope of the present study. We intend to expand our work to all 49 OGLE-II Galactic bulge fields covering a large range of $l$ and $b$ around the bar. A thorough analysis of all available data is underway and will be published elsewhere.

### ACKNOWLEDGMENTS

We are grateful to B. Paczyński for helpful comments and discussions. We are grateful to the OGLE team for providing us with all CCD images on which this paper is based. T.S. and L.E. acknowledge the financial support from the Nishina Memorial Foundation and from the Swiss National Science Foundation, respectively. This work was partly supported with the following grants to B. Paczyński: NSF grants AST-9820314 and AST-0204908, and NASA grants NAG5-12212, and grant HST-AR-09518.01A provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

### REFERENCES

Alcock, C. et al. 1997, ApJ, 486, 697
Alcock, C. et al. 2000a, ApJ, 541, 734
Alcock, C. et al. 2000b, ApJ, 542, 281
Aubourg, E. et al. 1993, Nature, 365, 623
Binney, J. & Tremaine, S. 1987, Galactic Dynamics (Princeton: NJ, Princeton University Press)
Blitz, L. & Spergel, D. N. S. 1991, ApJ, 379, 631
Bond, I. A. et al. 2001, MNRAS, 327, 868
Bond, I. A. et al. 2002, MNRAS, 331, L19
de Vaucouleurs, G. 1964. IAU Symp. 20. The Galaxy and the Magellanic Clouds, ed. F. J. Kerr & A. W. Rogers (Canberra: Australian Acad. Science, MSSSO), 195
Eyer, L. & Woźniak, P. R. 2001, MNRAS, 327, 601
Eyer, L. 2002, Acta Astronomica, 52, 241
Gould, A. 1996, PASP, 108, 465
Häfner, R. et al. 2000, MNRAS, 314, 433
Kiraga, M., & Paczyński, B. 1994, ApJ, 430, L101
Mao, S. & Paczyński, B. 2002, preprint [astro-ph/0207131]
Paczyński, B. 1996, ARA&A, 34, 419
Paczyński, B. & Stanek, K. Z. 1998, ApJ, 494, L219
Schechter, L., Mateo, M., & Saha, A. 1993, PASP, 105, 1342S
Stanek, K. Z. 1996, ApJ, 460, 37L
Stanek, K. Z. et al. 1994, ApJ, 429, L73
Stanek, K. Z. et al. 1997, ApJ, 477, 163
Stanek, K. Z. et al. 2000, Acta Astronomica, 50, 191
Sumi, T. et al. 2002, preprint [astro-ph/0207604]
Udalski, A. et al. 1993, Acta. Astron., 43, 289
Udalski, A. et al. 1994, Acta Astronomica, 44, 165
Udalski, A. et al. 2000, Acta Astronomica, 50, 1
Udalski, A. et al. 2002, Acta Astronomica, 52, 217

### Table 3. Mean values, errors and RMS of $\mu$ (mas yr$^{-1}$) for star samples discussed in the analysis.

| Population   | N   | $<\mu_l,\cos\delta>$ | RMS | $<\mu_\delta>$ | RMS | $<\mu_l>$ | RMS | $<\mu_b>$ | RMS |
|--------------|-----|----------------------|-----|----------------|-----|-----------|-----|-----------|-----|
| all          | 46961 | -0.046±0.022       | 4.69 | 0.091±0.020     | 4.39 | 0.054±0.021 | 0.86±0.021 |
| bright RCGs  | 3610 | 0.012±0.060        | 3.60 | 0.279±0.055     | 3.29 | 0.245±0.056 | 0.13±0.059 |
| faint RCGs   | 4979 | -0.871±0.053       | 3.76 | -0.930±0.048    | 3.37 | -1.247±0.049 | 0.259±0.052 |
| bright DSs   | 2004 | 1.669±0.082        | 3.67 | 2.140±0.084     | 3.78 | 2.697±0.084 | -0.310±0.083 |
| faint DSs    | 3011 | 1.413±0.081        | 4.47 | 2.229±0.078     | 4.26 | 2.639±0.079 | -0.045±0.080 |
| bright RGs   | 4911 | -0.501±0.067       | 4.68 | -0.356±0.060    | 4.24 | -0.565±0.062 | 0.242±0.065 |
| faint RGs    | 4770 | -0.516±0.080       | 5.55 | -0.378±0.072    | 4.97 | -0.592±0.074 | 0.244±0.078 |
Measurements of Streaming Motions of the Galactic Bar

**Figure 8.** Contour map and mean of the distribution of $\mu_\alpha$ and $\mu_\delta$ for bright (thick line and cross) and faint (thin line and cross) samples within three stellar populations defined in the analysis: RCGs (Top), DSs (Middle) and RGs (Bottom). Contours enclose 30, 60 and 80% of stars. Top-left corner corresponds to positive $l$ and bottom-right corner to negative $l$ direction.

**Figure 9.** The mean positional shift as a function of JD for RCGs (Top), DSs (Middle) and RGs (Bottom). The data points for each of the samples are shifted vertically for clarity and shown with different symbols: all (dot), bright (filled circle) and faint (open circle).

Udalski, A., Kubiak, M., & Szymański, M. 1997, Acta Astronomica, 74, 319
Wozniak, P. R., et al. 2001, Acta Astronomica, 51, 175
Wozniak, P. R., et al. 2002, Acta Astronomica, 52, 129