The Optical Gravitational Lensing Experiment: catalogue of stellar proper motions in the OGLE-II Galactic bulge fields

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ABSTRACT
We present a proper-motion (μ) catalogue of 5 080 236 stars in 49 Optical Gravitational Lensing Experiment II (OGLE-II) Galactic bulge (GB) fields, covering a range of −11° < l < 11° and −6° < b < 3°, the total area close to 11 deg². The proper-motion measurements are based on 138–555 I-band images taken during four observing seasons: 1997–2000. The catalogue stars are in the magnitude range 11 < I < 18 mag. In particular, the catalogue includes red clump giants and red giants in the GB, and main-sequence stars in the Galactic disc. The proper motions up to μ = 500 mas yr⁻¹ were measured with a mean accuracy of 0.8–3.5 mas yr⁻¹, depending on the brightness of a star. This catalogue may be useful for studying the kinematics of stars in the GB and the Galactic disc.

Key words: astrometry – Galaxy: bulge – Galaxy: centre – Galaxy: kinematics and dynamics – Galaxy: structure.

1 INTRODUCTION
The Galactic bulge (GB) is the nearest bulge in which individual stars can be studied in detail. A study of stellar populations and stellar dynamics in the bulge may help us understand how bulges formed, and help us understand their populations, gravitational potential and structure.

Measurements of proper motions with precise photometry might make it possible to separate the observed populations based on their kinematics. Such a study was first done by Spaenhauer, Jones & Whitford (1992) with photographic plates only for a few hundred of the brightest red giants in Baade’s window. Recently, a deeper study has been done by Kuijken & Rich (2002) with the Hubble Space Telescope (HST)/WFPC2 in Baade’s window.

Several groups have carried out gravitational microlensing observations toward dense stellar fields, such as the Magellanic Clouds, the Galactic Centre and disc. So far, hundreds of events have been found (EROS: Aubourg et al. 1993; OGLE: Udalski et al. 2000; Woźniak et al. 2001; MOA: Bond et al. 2001; Sumi et al. 2003), and thousands are expected in the upcoming years by MOA,1 OGLE-III2 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). 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. The observed high optical depth may be explained by the presence of the bar (Udalski et al. 1994; Alcock et al. 1997, 2000; Afonso et al. 2003; Popowski et al. 2003; Sumi et al. 2003); there is substantial evidence that the Galaxy has a bar at its centre (de Vaucouleurs 1964; Blitz & Spergel 1991; Kiraga & Paczynski 1994; Stanek et al. 1994, 1997; Häfner 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 GB 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 GB is small, about 0.2 mag

1 http://www.roe.ac.uk/~iab/alert/alert.html
2 http://www.astrow.edu.pl/~ogle/ogle3/ews/ews.html

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(Stanek et al. 1997; Paczynski & Stanek 1998). Their observed peak and width of the luminosity function are related to the distance and radial depth of the bar.

Furthermore, Mao & Paczynski (2002) suggested that there should be a difference in average proper motions of 1.6 mas yr$^{-1}$ between the bright and faint RCG subsamples, which are on average on the near and the far side of the bar, respectively, if their tangential streaming motion is 100 km s$^{-1}$. Following this suggestion, Sumi, Eyer & Wozniak (2003) measured the proper motion of bright and faint RCGs in one OGLE-II field in Baade’s window, and they found a difference of 1.5 ± 0.11 mas yr$^{-1}$.

To expand this analysis we measured proper motions in all 49 GB fields observed by the Optical Gravitational Lensing Experiment$^3$ II (OGLE-II; Udalski et al. 2000) for stars down to $I = 18$ mag, which is sufficiently deep to include RCGs. There are several earlier proper-motion catalogues of this general area (cf. USNO-B: Monet et al. 2003, Improved NTLT: Salim & Gould 2003 and Tycho-2: Høg et al. 2000). Though the area covered by our catalogue is relatively small, it reaches deeper and covers a wide range of proper motion ($\mu < 500$ mas yr$^{-1}$) with an accuracy as good as ~1 mas yr$^{-1}$. In Section 2 we describe the data. We present the analysis method in Sections 3 and 4. In Sections 5, 6 and 7 we describe the proper, zero-point problems in our catalogue. The discussion and conclusion are given in Section 8.

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 $\mu$m resulting in a 0.417 arcsec pixel$^{-1}$ scale. Images of the GB fields were taken in drift-scan mode at ‘medium’ readout speed with gain 7.1 e$^{-}$ ADU$^{-1}$ (where ADU is an analogue to digital unit) and readout noise of 6.3 e$^{-}$ scale. 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 found in Udalski, Kubiak & Szymański (1997).

In this paper we use 138–555 $I$-band frames of the BUL_SC1-49 fields. The centres of these fields are listed in Table 1. The time baseline is almost 4 yr. There are gaps between the observing seasons when the GB cannot be observed from the Earth, each about 3 months long. The median seeing is ~1.3 arcsec. We use the $V$ photometric maps of the standard OGLE template (Udalski et al. 2002) as the astrometric and photometric references.

Only about 70 per cent of the area of the BUL_SC1 field overlaps with the extinction map made by Stanek (1996). The extinction map covering all OGLE-II fields has been constructed by Sumi (2004).

3 ANALYSIS
The analysis in this work follows Sumi et al. (2003), except that our procedure makes it possible to detect high proper motions, extends to the limiting magnitude down to $I = 18$ mag and corrects the systematic effects. The standard OGLE template given by Udalski et al. (2002) serves as the fixed astrometric reference in our analysis. In order to treat frame distortions properly in the $y$-axis (declination) due to the drift-scan mode of observation, each OGLE-II field is divided into 64 subframes before processing. Subframes are 2048 × 128 pixels with a 14-pixel margin on each side.

We compute the pixel positions of stars in the images 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 measured and 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.

To treat spatial point spread function (PSF) variations properly, each 2048 × 128 pixel subframe is divided into four smaller chunks with a size of 512 × 128 pixels with a 14-pixel margin on each side. Then the positions of stars in all chunks are computed by DoPHOT. We use all stars with $I < 18$ mag (~400 of them, depending on the stellar density in each field) categorized by DoPHOT as isolated stars (marked as type = 1) in the following analysis. We do not use the data points categorized by DoPHOT as a star blended with other stars (marked as type = 3).

The stars in each of the chunks are combined into the original 2048 × 128 subframes. We cross-reference the stars in the template and other frames with a search radius of 0.5 pixels and derive the local transformation between these pixel coordinate systems for each subframe. We use a first-order polynomial to fit the transformation. The resulting piecewise transformation adequately converts pixel positions to the reference frame of the template. Typical residuals are at the level of 0.08 pixels for bright stars ($I < 16$) and 0.2 pixels for all stars ($I < 18$).

By using these transformation matrices, we cross-reference the stars in the template and other frames with a search radius of 1.0 pixels instead of 0.5 pixels used in Sumi et al. (2003) to increase the range of detectable high-proper-motion objects. We estimate that the probability of misidentification in this search radius is negligible (0.26 per cent).

We have found that there are systematic differences in the mean positional shifts of stars from the template position ($dx$) and ($dy$) depending on time and pixel coordinate in $x$. We have measured the ($dx$) and ($dy$) of the stars in 81 strips ($X = 0 \sim 80$) centred at equal intervals in the $x$-coordinate in the range 0 $\leq x \leq 2048$ with a width of $\pm 25$ pixels. Each strip contains typically ~2000 stars. In the upper panel of Fig. 1 we show ($dx$) as a function of time for the strip $X = 40$ ($x = 1024 \pm 25$ pixels) in BUL_SC2. We can see the big jump at JD = 245 1041 (indicated by a vertical dashed line) where the exposure time of OGLE-II in the GB fields has been changed from 87 to 99 s in the middle of the 1998 season, on August 15. In the upper panel of Fig. 2 we show typical mean positional shifts in $x$, ($dx$), of stars in strips in BUL_SC2 as a function of pixel coordinate $x$. The filled and open circles represent the ($dx$) of the frame taken at JD = 245 0887.822 (before the jump) and 2451336.769 (after the jump), respectively. There are also systematics in ($dy$) with the level of 0.04 pixels. We cannot see any such systematics as a function of the $y$ pixel coordinate. Because of the good coincidence between the jump and the change in the drift-scan rate that determines the effective exposure time, the bulk of the systematics may be caused by the change in drift-scan rate. However, we do not know the detailed reasons behind this at the present time.

Even within the period before and after the jump, the shapes of Fig. 2 differ from time to time and from field to field at the level of 0.04 pixels. By interpolating these curves of ($dx$) and ($dy$) as a function of $x$ for each frame (time) of each field, we correct $dx$ and $dy$ for each star and frame. In the lower panels of Figs 1 and 2, we show the same plots after this systematic correction. This procedure

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$^3$ see http://www.astrouw.edu.pl/~ogle or http://bulge.princeton.edu/~ogle

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is based on the assumption that average proper motions of a large number of stars in separate groups of columns (i.e. different values of $X$) should be the same. Note that the integral of the curves shown in Fig. 2 over all $x$-columns is unity, as this corresponds to the average position of all stars.

An example of time-dependence of the position for a star with a moderate detectable proper motion is shown in Fig. 3 with filled circles. To measure the proper motions in right ascension ($\mu_\alpha \equiv \mu_\alpha \cos \delta$) and in declination ($\mu_\delta$), we fit the positions as a function of time $t$ with the following formula:

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

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

where $a$ is the coefficient of differential refraction, $z$ is the zenith angle, and $C$ is the angle between the line joining the star and zenith and the line joining the star with the South Pole, and $\alpha_0$ and $\delta_0$ are constants. The parameter $a$ is a function of the apparent star colour.
We neglect the parallactic motion due to the Earth’s orbit because its effect is strongly degenerate with the effect of differential refraction for stars in the direction of the GB (Eyer & Woźniak 2001).

In Fig. 3 we present with solid lines and open circles the best-fitting model for the proper motion ($\mu_\alpha, \mu_\delta$) and positions allowing for the differential refraction, respectively. As shown in this figure, the parameters for this object are: field SC5-1-6, which means that this object is in the OGLE-II field BUL_SC5, and chunk ($X_{\text{chunk}}, Y_{\text{chunk}}$) = (1, 6), OGLE ID = 5935, $I = 14.093$, $V - I = 1.260$, the number of data points $N = 392$, proper motion ($\mu_\alpha, \mu_\delta$) = (1.19 (0.41), 0.94 (0.35)) (mas yr$^{-1}$) with 1$\sigma$ errors in brackets. The differential refraction coefficient is $a = -22.42$ mas.

We computed $\sigma_\alpha$, $\delta_\delta$, $\mu_\alpha$, $\mu_\delta$ and $a$ for all stars used to transform the coordinate systems (approximately the number of fields times the number of chunks times the typical number of stars per chunk, i.e. 49 x 256 x 400). In cases where the star is measured in the overlap region of more than one chunk of a given field, the data set with the largest number of points is selected. Stars with fewer than 20 data points are rejected. The whole BUL_SC1 catalogue was recomputed in this analysis because the catalogue presented by Sumi et al. (2003) contains only 70 per cent of this field.

Our catalogue contains 5 080 236 stars, which is 79.8 per cent of all objects with $I \leq 18$ mag in the original OGLE template (Udalski et al. 2002). 7 per cent of these stars do not have any $V$-band photometry. The missing $V$-band photometry of stars can be estimated from the differential refraction coefficient because there is good correlation between the differential refraction coefficient $a$ and the apparent $V - I$ colour for stars (see Fig. 8 below), provided they belong to the same population as that of the majority.

We have measured the mean proper motions of stars in the Galactic bulge defined in the ellipse in the colour–magnitude diagram (CMD) in Fig. 4, where the extinction and reddening are corrected by using the extinction map of Sumi (2004). The ellipse is located at the centre of the RCGs estimated in Sumi (2004) plus 0.4 mag in $I$ and have semimajor and semiminor axes of 0.9 mag and 0.4 mag, respectively. This ellipse includes RCGs and red giants in the GB. Here we chose only objects whose proper-motion accuracy is better than 2.5 mas yr$^{-1}$. These mean proper motions of stars in the GB are assumed to be constant within each field. In Fig. 5 we show these measured mean proper motions of stars in the GB as a function of $x$ (upper panel) and after systematic correction (lower panel). We can see how well the systematic distortions are corrected. Note that our instrumental reference frame is defined by all stars, and this is why the average proper motion of stars in the GB is not zero.

### 4 HIGH-PROPER-MOTION OBJECTS

The detectability of high proper motions is limited by the search radius used for cross-identification of stars on all images. The search radius, 1 pixel yr$^{-1}$, corresponds to $\sim$ 400 mas yr$^{-1}$. Objects with
The OGLE-II Galactic bulge fields

Figure 4. Colour–magnitude diagram of stars with $\sigma_\mu < 2.5$ mas yr$^{-1}$ in BUL_SC2. $I_0$ and $(V-I)_0$ are extinction-corrected $I$-band magnitude and $V-I$ colour. The stars in GB are defined within the ellipse centred at the centre of RCGs plus 0.4 mag in $I$.

Figure 5. Upper panel: the mean proper motions in $x$ (filled circles) and in $y$ (open circles), for stars in 50-pixel strips in BUL_SC2 as a function of pixel coordinate $x$. Lower panel: the same figure as above after systematic correction.

$\mu \geq 100$ mas yr$^{-1}$ cannot be identified over the full four-year long observing interval of OGLE-II, as they move out of the search radius. In order to be able to follow fast-moving stars over four observing seasons we made additional astrometry for objects for which preliminary estimates gave a proper motion $\mu \geq 100$ mas yr$^{-1}$. Whenever a star moved more than 0.4 pixels from the previous search centre we moved that centre to the median location of the last three data points. This procedure was adopted when it allowed us to locate the star in a larger number of CCD images.

We show the positional movement of one of the highest-proper-motion objects in Fig. 6 and images at 1997 and at 2000 in Fig. 7. This star has relatively fewer data points because this star is over-

Figure 6. Same plots as Fig. 3 for ID = 133638 ($V-I = 0$) in OGLE-II field BUL_SC42, one of the highest-proper-motion stars. Filled circles represent the actual positions and open circles are the positions corrected for differential refraction, with an offset of +1.5 pixel. Solid lines indicate a model fit for the proper motion $(\mu_\alpha, \mu_\delta) = (-261.19 (2.51), -436.90 (1.2))$ (mas yr$^{-1}$) with 1σ errors in bracket. The differential refraction coefficient is $a = 26.04$ mas, which indicates the star is very red. This star does not have $V$-band magnitude because of the high proper motion. The photometries of the star obtained by hand relatively to the neighbouring stars are: $I = 11.70$, $V-I = 2.86$.

Figure 7. Images of the high-proper-motion star in Fig. 6, i.e. ID = 133638 in OGLE-II field BUL_SC42, at 1997 April 19 (left) and at 2000 September 30 (right).
difference of the population. In BUL_SC5, the majority in this colour region are RCGs and red-giant-branch stars, but red supergiants in BUL_SC42. So this disagreement might be because this object is a nearby very red dwarf of M4-5 spectral type, not typical for this catalogue.

5 CATALOGUE

A sample for our catalogue of proper motions is shown in Table 2. The complete list of all 5 080 236 stars is available in electronic format via anonymous ftp. The list contains the star ID, the numbers $\mu_{\alpha}$ and $\mu_{\delta}$ and in Galactic coordinate $\mu_{l}$ and $\mu_{b}$ with their errors, differential refraction coefficient $\sigma_I$, standard deviation (Sdev) of data points in the fitting, equatorial coordinates $\alpha_2000$, $\delta_2000$, in 2000, apparent $I$-band magnitude and $V-I$ colour, pixel coordinates on CCD $x$ and $y$, and the position of chunk $X_c$ and $Y_c$ to which this object belongs. ID, 2000 coordinates, $I$ and $V-I$ for each object are identical to those in Udalski et al. (2002). If the object does not have $V$-band photometry the $V-I$ colour is written as 9.999.

Note that the number of data points $N$ differs from star to star even if they have similar brightness. This is because some are near the edge of the CCD image or CCD defects, and others are affected by blending. We use the positions which are categorized as a single isolated star by DOPHOT. Hence, blended stars cannot be measured when the seeing is poor.

In Fig. 8 we present a colour–magnitude diagram for stars in OGLE field BUL_SC5, which is one of the most reddened OGLE-II fields. We also show the correlation between the differential refraction coefficient $a$ and the apparent $V-I$ colour for stars with $I < 16$ in this field. This correlation for other fields is similar, but it has a slight dependence on the population of the majority of stars in each field. In Fig. 9, we plot the uncertainties in $\mu_{\alpha}$ ($\sigma_{\mu_{\alpha}}$, upper panel), in $\mu_{\delta}$ ($\sigma_{\mu_{\delta}}$, middle panel) and difference between them ($\sigma_{\mu_{\alpha}} - \sigma_{\mu_{\delta}}$, lower panel) in BUL_SC5 as a function of the apparent $I$-band magnitude. In the lower panel, where open circles represent mean values for each 1-mag bin, we can see that $\sigma_{\mu_{\alpha}}$ is systematically larger than $\sigma_{\mu_{\delta}}$ at $\sim 0.1$ mas yr$^{-1}$ level. We see the same trend in all our fields. This trend is expected from the residual scattering due to the systematic correction and the differential refraction which is large in the direction of $\alpha$. The mean uncertainties $\langle \sigma_{\mu} \rangle \equiv (\sqrt{\sigma_{\mu_{\alpha}}^2 + \sigma_{\mu_{\delta}}^2})$ with 2$\sigma$ clipping as a function of $I$ are listed in Table 1. Note that the accuracy of proper motions in our catalogue is better than 1 mas yr$^{-1}$ for $I < 12$. In Fig. 10 we present a colour–magnitudes diagram of a quarter of the analysed stars in OGLE-II field BUL_SC5. Lower: correlation between the differential refraction coefficient $a$ and the apparent colour for stars with $I < 16$ in this field.

Figure 8. Upper: colour–magnitude diagram of a quarter of the analysed stars in OGLE-II field BUL_SC5. Lower: correlation between the differential refraction coefficient $a$ and the apparent colour, pixel $a$ (pixel) and $\alpha$ (mas).

6 ZERO-POINT

The proper motions in our catalogue are relative values. We need quasi-stellar objects (QSOs) behind our fields to define the zero-point of our proper motions in the inertial frame. However, we can get rough information about the zero-point of our proper motions by measuring the average proper motion of stars located in the GB, which is presumably close to absolute proper motion of the Galactic Centre (GC).

We select stars in the GB defined in Fig. 4. Here we choose only objects whose proper-motion accuracy is better than 2.5 mas yr$^{-1}$. We divide them into bins with a width of $\Delta I = 0.1$ mag in $I$-band magnitude and take the mean of their proper motions for each bin. We plot these mean proper motions ($\mu_{l,b}$) as a function of $I$ for BUL_SC5 in Fig. 11. In this figure we can see the streaming motion of bright ($I \sim 14.1$) and faint ($I \sim 14.7$) RCGs in $\mu_{l}$. The proper motion of red giants ($I > 15$) is the same as the average

4 ftp://ftp.astrouw.edu.pl/ogle/ogle2/proper_motion/
ftp://bulge.princeton.edu/ogle/ogle2/proper_motion/
To measure the proper motion of the GC, $\mu_{\alpha}$ and $\mu_{\delta}$ are in average distribution and kinematics.

Table 2 A sample of proper-motion catalogue for BULSC2. The full table is available at http://www.blackwellpublishing.com/products/journals/suppmat/mnr/mn7457/mnr7457sm.htm

| ID  | N  | $\mu_{\alpha}$ | $\sigma_{\mu_{\alpha}}$ | $\mu_{\delta}$ | $\sigma_{\mu_{\delta}}$ | $\mu_{\beta}$ | $\sigma_{\mu_{\beta}}$ | $\mu_{\rho}$ | $\sigma_{\mu_{\rho}}$ | $\alpha$ | Sdev | $\delta_{\alpha}$ | $\delta_{\delta}$ | $I$ | $V - I$ | $x$ | $y$ | $X_c$ | $Y_c$ |
|-----|----|---------------|-----------------|---------------|-----------------|---------------|-----------------|---------------|-----------------|---|-----|---------------|---------------|---|--------|---|---|-----|-----|
| 13213 | 203 | 2.96 | 0.90 | -0.44 | 0.63 | 1.06 | 0.70 | -2.80 | 0.84 | 0.69 | 13.02 | 270.99213 | -29.24292 | 15.282 | 1.522 | 62.52 | 904.72 | 1 | 7 |
| 13214 | 258 | 1.09 | 0.66 | -2.03 | 0.41 | -1.24 | 0.48 | -1.94 | 0.61 | -0.88 | 10.16 | 271.03837 | -29.24297 | 15.507 | 1.716 | 413.60 | 904.92 | 1 | 8 |
| 13215 | 255 | -1.71 | 0.68 | -1.75 | 1.01 | -4.98 | 0.94 | -0.82 | 0.77 | 11.18 | 271.04729 | -29.24297 | 15.572 | 1.599 | 481.45 | 904.94 | 1 | 7 |
| 13216 | 247 | -0.11 | 0.67 | -1.46 | 0.51 | -1.33 | 0.55 | -0.62 | 0.64 | -0.57 | 10.95 | 271.00104 | -29.24281 | 15.635 | 1.990 | 130.10 | 905.70 | 1 | 7 |
| 13217 | 250 | -3.44 | 0.83 | -0.74 | 0.76 | -2.32 | 0.78 | 2.64 | 0.81 | -2.72 | 14.72 | 271.00654 | -29.24286 | 15.768 | 1.746 | 171.88 | 905.41 | 1 | 7 |
| 13218 | 264 | 1.49 | 1.01 | -0.30 | 0.66 | -0.15 | 0.94 | -3.97 | 0.45 | 16.19 | 271.04246 | -29.24286 | 14.960 | 1.711 | 444.59 | 905.97 | 1 | 8 |
| 13219 | 263 | -3.31 | 0.91 | -1.75 | 0.39 | -3.14 | 0.56 | 2.04 | 0.82 | -2.80 | 13.20 | 271.02271 | -29.24231 | 15.132 | 1.931 | 294.82 | 910.42 | 1 | 8 |
| 13220 | 247 | -1.11 | 0.78 | -4.67 | 1.41 | -4.62 | 1.29 | -1.31 | 0.97 | 2.30 | 20.88 | 270.99650 | -29.24206 | 15.436 | 1.644 | 95.64 | 912.22 | 1 | 7 |
| 13221 | 262 | -3.98 | 0.55 | -6.50 | 0.50 | -7.62 | 0.51 | 0.31 | 0.54 | 0.29 | 9.87 | 271.01058 | -29.24183 | 15.310 | 1.853 | 202.60 | 914.42 | 1 | 8 |
| 13222 | 245 | 2.25 | 1.11 | -7.76 | 1.14 | -5.68 | 1.13 | -5.75 | 1.12 | 5.67 | 20.22 | 271.04275 | -29.24197 | 15.369 | 1.903 | 446.73 | 913.83 | 1 | 8 |
| 13223 | 189 | -2.72 | 0.87 | 0.31 | 0.64 | -1.06 | 0.70 | 2.53 | 0.82 | -3.43 | 12.55 | 270.99100 | -29.24144 | 15.874 | 1.915 | 53.69 | 917.54 | 1 | 8 |
| 13224 | 131 | 0.83 | 0.88 | -3.41 | 1.01 | -2.57 | 0.98 | -2.39 | 0.91 | 1.48 | 13.38 | 270.98617 | -29.24125 | 15.460 | 1.795 | 17.09 | 919.06 | 1 | 8 |
| 13225 | 248 | 0.32 | 0.53 | -5.23 | 0.68 | -4.41 | 0.65 | -2.83 | 0.57 | 0.41 | 11.08 | 271.03579 | -29.24092 | 15.015 | 1.690 | 394.10 | 922.69 | 1 | 8 |
| 13226 | 262 | 0.45 | 0.60 | 1.12 | 0.62 | 1.20 | 0.62 | 0.15 | 0.61 | 0.31 | 11.51 | 271.00475 | -29.24047 | 15.208 | 1.909 | 158.16 | 926.03 | 1 | 8 |
| 13227 | 249 | -1.94 | 0.92 | -6.90 | 0.98 | -6.97 | 0.97 | -1.67 | 0.93 | 0.10 | 17.20 | 270.99608 | -29.24036 | 15.402 | 1.876 | 92.42 | 926.87 | 1 | 8 |
| 13228 | 264 | 3.89 | 0.57 | 3.85 | 0.60 | 5.26 | 0.59 | -1.52 | 0.58 | -0.14 | 11.09 | 271.02446 | -29.24042 | 15.082 | 1.757 | 307.89 | 926.93 | 1 | 8 |
| 13229 | 249 | 0.82 | 0.76 | -0.58 | 0.68 | -0.11 | 0.70 | -1.00 | 0.74 | -1.17 | 13.26 | 271.03533 | -29.24047 | 15.090 | 1.850 | 390.64 | 926.65 | 1 | 8 |
| 13230 | 200 | 2.53 | 1.72 | 11.04 | 1.50 | 10.87 | 1.56 | 3.17 | 1.67 | 0.86 | 26.09 | 271.00042 | -29.24025 | 15.608 | 1.658 | 125.33 | 928.07 | 1 | 8 |

Figure 9. Uncertainties in $\sigma_{\mu_{\alpha}}$ (upper panel), $\sigma_{\mu_{\delta}}$ (middle panel), and the difference between them, $\sigma_{\mu_{\alpha}} - \sigma_{\mu_{\delta}}$ (lower panel) in OGLE-II field BULSC2 as a function of the 4-band magnitude. In the lower panel, where open circles represent mean value for each mag bin, we can see that $\sigma_{\mu_{\delta}}$ is systematically larger than $\sigma_{\mu_{\alpha}}$ by ~0.1 mas yr$^{-1}$. Level.
for fainter stars, we take a mean of these \(\langle \mu_{1,3} \rangle\) without weighting by their errors. This provides an estimate that is more reliable than taking the mean proper motion of all individual stars. The measured \(\mu_{1,3}\) and \(\mu_{3,5}\) are shown as a solid and dashed line for BUL\_SC2 in Fig. 11 and listed for other fields in Table 3 along with those in equatorial coordinates \((\mu_{3,5}, \mu_{3,8})\). Table 3 is also available in electronic format via anonymous ftp with the main catalogue (see Section 5).

The proper-motion measurements in our catalogue can be transformed to the inertial frame by the formulae

\[
\begin{align*}
\mu_{1,3}\text{OGLE} &= \mu_{1,3}\text{GC} - \mu_{1,3}\text{GC, inert} \\
\mu_{3,5}\text{OGLE} &= \mu_{3,5}\text{GC} - \mu_{3,5}\text{GC, inert}.
\end{align*}
\]

Here \((\mu_{3,5}, \mu_{3,8})\) is a mean of \(\langle \mu_{1,3}\rangle\) with standard deviations, is the expected proper motion of the GC relative to the inertial frame, assuming a flat rotation curve of \(v_r \approx 220 \text{ km s}^{-1}\), the distance between the GC and the Sun of \(R_0 = 8.0 \text{ kpc}\) (Eisenhauer et al. 2003) and solar velocity \((v_{1,3}, v_{3,8}) = (5.25 \text{ km s}^{-1}, 7.17 \text{ km s}^{-1})\) relative to the local standard of rest (RSL) (Dehnen & Binney 1998). This transformation gives us crude absolute proper motions, while it gives us very good relative zero-points from field to field as we show later.

The reader can apply this transformation formula to our catalogue to get the value in the inertial frame. We did not apply this transformation to the catalogue because the transformation to the inertial frame can be improved with the QSOs to be discovered behind our fields in the future.

To check our measurements we cross-identified stars in our catalogue with the Tycho-2 catalogue (Høg et al. 2000). We selected from our catalogue objects with proper motions higher than 10 mas yr\(^{-1}\) and measured with a significance above \(3\sigma\), to avoid misidentification. Most high-proper-motion stars in Tycho-2 are saturated in OGLE images. We found 65 Tycho-2 stars in our catalogue and their proper motions, \(\mu_1\) (thin line) and \(\mu_3\) (thick line), are presented in Fig. 12. Here OGLE proper motions have been transformed into the inertial frame by equations (3) and (4). We can see a very good correlation between OGLE and Tycho-2 measurements. Dashed lines indicate \(\mu_{\text{OGLE}} = \mu_{\text{Tycho-2}}\), and solid lines represent the best fit with fixed unit slope and a possible offset. A good correspondence between Tycho-2 and OGLE-II proper motions gives us a certain confidence in our measurements. Slightly larger offsets in \(\mu_3\) imply that the error in absolute proper motion is at a level of 1 mas yr\(^{-1}\), which can be improved by using QSOs in the near future.

We also compared the measurements in BUL\_SC1 made by Sumi et al. (2003) (hereafter SC1) with the proper motions presented in this paper, for which our measurements are above the 10\(\sigma\) level of accuracy. The two sets of proper motions for 1368 cross-identified stars are shown in Fig. 13 together with the best-fitting line. The offset between the two sets, and the differences between individual measurements, are within estimated errors. Note that the scale is different from that in Fig. 12. The large reduced \(\chi^2\) in \(\mu_3\) is because Sumi et al. (2003) did not correct systematic distortions (see Section 3), though their systematic distortions have been reduced at a level of 2 mas yr\(^{-1}\) by dividing images into small chunks.

We compared the measurements done by us in one of the overlap regions, between fields BUL\_SC1 and BUL\_SC45. The proper motions of 115 cross-identified stars, and the best-fit with a small offset between zero-points, are presented in Fig. 14. Here proper motions have been transformed into the inertial frame by equations (3) and (4). Good correlations between them with rather small zero-point offsets, \(\mu_{\text{SC1}} - \mu_{\text{SC45}} = 0.16 \text{ mas yr}^{-1}\) and \(\mu_{\text{SC1}} - \mu_{\text{SC45}} = -0.07 \text{ mas yr}^{-1}\), give us a certain confidence in our measurements and in equations (3) and (4) in terms of the relative zero-point. The scatter is also consistent with the estimated errors.

7 POSSIBLE PROBLEMS

There can be various problems associated with proper motions of variable stars. Our fields are very crowded, hence many stars may be blended. In the case of blending we measure an average position of a blend of several stars within a seeing disc. If a variable star is blended with other stars which have slightly different positions within a seeing disc, the average position of the blended image may change while one component of the blend varies. This change might mimic a proper motion.

As an example we present the time variation of the position of a very long time-scale microlensing-event candidate (Smith 2003) in the top panel of Fig. 15. The I-band light curve of this event is shown in the bottom panel of Fig. 15 (ID = 2859 in the variable star catalogue of Woźniak et al. 2002). In the top panel we can see an apparent proper motion in the first year which is coincident with the fading of the apparent brightness, as shown in the bottom panel. After the second year the proper motion seems to be small, and the position data points are sparse, which coincides with the low brightness of the star and may reflect the presence of a blend – in poor seeing DOPHY cannot resolve the two stars, hence there are very few data points in the upper panel. The blend was actually found in the higher-resolution OGLE-III images in 2002.

A plausible interpretation is that the microlensed star was brighter than the nearby faint ‘companion’ star in 1997, but by 2000 it became the fainter of the two. The position of the ‘companion’ is consistent with the direction of the apparent proper motion. The faint stars seem to have low proper motion. High-resolution observations are needed to understand this object fully.

As another example we present in Fig. 16 the time variation of the position of a star ID = 309705 in the OGLE-II field BUL\_SC39. Filled circles represent measured positions with type = 1 (used in this work), which were at a fixed location for the first three years.
but moved significantly in the fourth season. The star ID = 309705 identified these centroids at the edge of the search radius (y = −1) for the first three seasons and at the centre (y = 0) in the fourth season. On the other hand, the neighbouring star ID = 309653 which has a similar brightness of l = 14.8 and position of 0.18 pixels east (positive x) and −1.89 pixels south (negative y), identified the same centroids at the edge of the search radius (y = −1).

To see the details of this object, in Fig. 16 we also plot the position measurements which are categorized as a star blended with other stars (type = 3, which are not used in this work) by DoPHOT for this star (crosses) and for a neighbouring star ID = 309653 (dots), which are shifted by +0.18 pixel in x and −1.89 pixel in y, i.e. these dots are as they are on the CCD, relative to ID = 309705. We can see that these positions (crosses and dots) are identified around y = 0 (ID = 309705) and −2 (ID = 309653), respectively, with filled circles in-between them. We also show the I-band light curves of ID = 309705 (middle panel) and ID = 309653 (bottom panel) in Fig. 16. We can see ID = 309705 is constant during four seasons.
Figure 12. Comparison of proper motions $\mu_\alpha$ (thin line) and $\mu_\delta$ (thick line) for 65 stars cross-identified in our catalogue and in the Tycho-2 catalogue. The proper motions in our catalogue are transformed to the inertial frame by equations (3) and (4). Dashed lines indicate $\mu_{\text{OGLE}} = \mu_{\text{Tycho-2}}$, and solid lines represent the best fit with the offsets: $\mu_{\alpha \text{OGLE}} - \mu_{\alpha \text{Tycho-2}} = -0.23$ mas yr$^{-1}$ and $\mu_{\delta \text{OGLE}} - \mu_{\delta \text{Tycho-2}} = 0.99$ mas yr$^{-1}$. $\mu_\alpha$ are shifted by +30 mas yr$^{-1}$ for clarity.

Figure 13. Same as Fig. 12 for 1368 stars cross-identified in BUL_SC1 by Sumi et al. 2003 (hereafter SC1′) and in SC1 by this work, measured with better than 10σ level accuracy. Proper motions are transformed into the value in the inertial frame by equations (3) and (4). Dashed lines indicate $\mu_{\text{SC1}} = \mu_{\text{SC1′}}$, and solid lines represent the best fit with the offsets: $\mu_{\alpha \text{SC1}} - \mu_{\alpha \text{SC1′}} = 0.11$ mas yr$^{-1}$ and $\mu_{\delta \text{SC1}} - \mu_{\delta \text{SC1′}} = -0.03$ mas yr$^{-1}$. $\mu_\alpha$ in SC1 are shifted by +30 mas yr$^{-1}$ for clarity. Note that the scale is different from that in Fig. 12.

Figure 14. Same as Fig. 12 for 115 stars cross-identified in the overlap region between OGLE-II fields BUL_SC1 and BUL_SC45, and measured with better than 5σ level accuracy. Proper motions are transformed into the value in the inertial frame by equations (3) and (4). Dashed lines indicate $\mu_{\text{SC1}} = \mu_{\text{SC45}}$, and solid lines represent the best fit with the offsets: $\mu_{\alpha \text{SC1}} - \mu_{\alpha \text{SC45}} = 0.16$ mas yr$^{-1}$ and $\mu_{\delta \text{SC1}} - \mu_{\delta \text{SC45}} = -0.07$ mas yr$^{-1}$. $\mu_\alpha$ in SC45 are shifted by +30 mas yr$^{-1}$ for clarity.

but ID = 309653 suddenly faded during the fourth season. This is likely to be a R CrB type variable.

The simplest interpretation is as follows: the small number of data points in the seasons 1997–99 indicates that DoPHOT found that object which is a composite of these two stars only on the bad-seeing frames as a single star with type = 1; in other cases they are separated but categorized as blended, type = 3. In 2000 when the star ID = 309653 faded, the centroid of the composite moved and finally the star ID = 309705 became a ‘single’ star with type = 1. So the number of data points is large in 2000.

Proper motions of variable stars may have their errors increased not only because of the variable contribution of blending, but also because variable stars may change colours, and therefore the coefficient of differential refraction may also change. In rare cases of very long-period variables this may be noticeable. Note that we do not treat this kind of object in a special way, so the reader must be careful when using our catalogue in studies of variable stars.

The effect of blending changes with seeing may contribute to the scatter of data points, but it is not likely to have a seasonal effect. Hence, we think that seeing variations are not a major problem.

The probability of blending is much larger for fainter stars, in particular those close to $I = 18$ mag. This may produce a bias in their proper motions, most likely reducing their formal proper motion, as the blended stars may have a different proper-motion vector, so the average value is likely to be reduced. We also do not provide a special treatment for this kind of object, so the reader must be careful when using our catalogue for faint stars.

8 DISCUSSION AND CONCLUSION

We have measured proper motions for 5 080 236 stars in all 49 OGLE-II GB fields, covering a range of $-11^\circ < l < 11^\circ$ and $-6^\circ < b < 3^\circ$. Our catalogue contains objects with proper motions up...
to $\mu = 500$ mas yr$^{-1}$ and $I$-band magnitudes in the range $11 \leq I \leq 18$. The accuracy of proper motions in our catalogue is better than 1 mas yr$^{-1}$ for $12 < I < 14$.

One should keep in mind that all measurements of $\mu$ presented here are not absolute, but relative to the astrometric reference frame which is roughly that of the Galactic Centre (GC) with a small offset seen in the lower panel of Fig. 5. However, as demonstrated in Section 6, by using the crude estimation for the proper motion of the GC in our reference frame and formulae (3) and (4), we can obtain crude proper motions in an inertial frame. From the comparison with these inertial values and the Tycho-2 catalogue, this transformation seems to work well with errors at a level of 1 mas yr$^{-1}$. From comparison of $\mu$ measured in the overlap region of fields BUL_SC1 and BUL_SC45 (Fig. 14), this transformation works very well in the relative offset from field to field. These zero-points for proper motions can be improved by using background quasars which may be detected in the near future using the OGLE-II variability catalogue (Eyer 2002; Woźniak et al. 2002; Dobrzycki et al. 2003).

As demonstrated by Sumi et al. (2003), the proper motions based on OGLE-II data can be used to detect clearly the presence of a strong streaming motion (rotation) of stars in the Galactic bar. While the reference frame established from all stars is not well defined with respect to the inertial frame, the relative motions of groups of stars within a given field are well determined.

Though our primary goal is to constrain the Galactic bar model with the future analysis of our catalogue, we provide proper motions for all stars with $I < 18$ mag in all 49 OGLE-II GB fields because...
this catalogue might be useful for a variety of projects. An analysis of the catalogue is beyond the scope of the present study.

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REFERENCES

Afonso C. et al., 2003, A&A, 404, 145
Alcock C. et al., 1997, ApJ, 486, 697
Alcock C. et al., 2000, ApJ, 541, 734
Aubourg E. et al., 1993, Nat, 365, 623
Blitz L., Spergel D. N. S., 1991, ApJ, 379, 631
Bond I. A. et al., 2001, MNRAS, 327, 868
de Vaucouleurs G., 1964, in Kerr F. J., Rogers A. W., eds, IAU Symp. 20, The Galaxy and the Magellanic Clouds. Australian Acad. Science, Canberra, p. 195
Dehnen W., Binney J. J., 1998, MNRAS, 298, 387
Dobrzycki A., Macri L. M., Stanek K. Z., Groot P. J., 2003, AJ, 125, 1330
Eisenhauer F., Schoedel R., Genzel R., Ott T., Tecza M., Abuter R., Eckart A., Alexander T., 2003, ApJ, 597, L121
Eyer L., 2002, Acta Astron., 52, 241
Eyer L., Woźniak P. R., 2001, MNRAS, 327, 601
Gould A., 1996, PASP, 108, 465
Hafner R., Evans N. W., Dehnen W., Binney J., 2000, MNRAS, 314, 433
Høg E. et al., 2000, A&A, 355, L27
Kiraga M., Paczynski B., 1994, ApJ, 430, L101
Kuijken K., Rich R. M., 2002, AJ, 124, 2054
Mao S., Paczynski B., 2002, MNRAS, 337, 895
Monet D. et al., 2003, AJ, 125, 984
Paczynski B., 1996, ARA&A, 34, 419
Paczynski B., Stanek K. Z., 1998, ApJ, 494, L219
Popowski P., 2003, in Valls-Gabaud D., Kneib J.-P., eds, in Gravitational Lensing: A Unique Tool For Cosmology, in press (astro-ph/0304464)
Salim S., Gould A., 2003, ApJ, 582, 1011
Schechter L., Mateo M., Saha A., 1993, PASP, 105, 1342S
Smith M. C., 2003, MNRAS, 343, 1172
Spaenhauer A., Jones B. F., Whitford A. E., 1992, AJ, 103, 297
Stanek K. Z., 1996, ApJ, 460, 37L
Stanek K. Z., Mateo M., Udalski A., Szymański M., Kaluzny J., Kubík M., 1994, ApJ, 429, L73
Stanek K. Z., Udalski A., Szymański M., Kaluzny J., Kubík M., Mateo M., Krzemiński W., 1997, ApJ, 477, 163
Udalski A., Mateo M., Udalski A., Szymański M., Kaluzny J., Kubík M., Mateo M., Krzemiński W., 1997, ApJ, 477, 163
Udalski A., Mateo M., Udalski A., Szymański M., Kaluzny J., Kubík M., Mateo M., Krzemiński W., 1997, ApJ, 477, 163
Udalski A., Kaluzny J., Wysocka A., Thompson I., 2000, Acta Astron., 50, 191
Sunni T., 2004, MNRAS, in press (astro-ph/0309206)
Sunni T., Eyer L., Woźniak P. R., 2003, MNRAS, 340, 1346
Sunni T. et al., 2003, ApJ, 591, 204
Udalski A., Szymański M., Kaluzny J., Kubík M., Krzemiński W., Mateo M., Preston G., Paczyński B., 1993, Acta. Astron., 43, 289
Udalski A. et al., 1994, Acta Astron., 44, 165
Udalski A., Zebruk K., Szymański M., Kubík M., Pietrzyński G., Soszyński I., Woźniak P., 2000, Acta Astron., 50, 1
Udalski A. et al., 2002, Acta Astron., 52, 217
Udalski A., Kubík M., Szymański M., 1997, Acta Astron., 74, 319
Woźniak P. R., Udalski A., Szymański M., Kubík M., Pietrzyński G., Soszyński I., Zebruk K., 2001, Acta Astron., 51, 175
Woźniak P. R. et al., 2002, Acta Astron., 52, 129

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