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Variability-selected QSO candidates in OGLE-II Galactic bulge fields

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ABSTRACT

We present 97 QSO candidates in 48 Galactic bulge fields of the Optical Gravitational Lensing Experiment II (OGLE-II) covering $\sim$11 deg^2, which are selected via their variability. We extend light curves of variable objects which were detected in a 3-yr baseline in the OGLE-II variable star catalogue to fourth year. We search for objects that are faint ($16 < I_0 < 18.5$) and slowly variable over 4 yr in this catalogue by using the variogram/structure function. Finding the QSOs in such stellar-crowded and high extinction fields is challenging, but should be useful for the astrometric reference frame. Spectroscopic follow-up observations are required to confirm these QSO candidates. Follow-up observations are being prepared for four of these fields (BUL_SC1, 2, 32 and 45). Follow-up observations for other fields are strongly encouraged. The complete list and light curves of all 97 candidates are available in electronic format at http://www.astro.princeton.edu/ sumi/QSO-OGLEII/.

Key words: stars: variables: other – Galaxy: bulge – Galaxy: centre – quasars: general.

1 INTRODUCTION

QSOs have been found by a variety of different methods, mostly using optical photometry and spectroscopy, but also through their radio morphology and X-ray emission properties.

QSO searches were usually avoided in areas where source crowding was a problem, for example the Galactic plane or the direction of nearby galaxies, such as the Magellanic Clouds. High spatial resolution of the *Chandra* X-ray Observatory limited source confusion problems for the X-ray based searches. Dobrzycki et al. (2002) found several quasars behind the LMC and SMC, including four quasars behind the dense parts of the LMC bar by spectroscopic observations of the OGLE optical counterpart of *Chandra* X-ray sources.

Another efficient method of searching for quasars is based on optical variability (Hawkins 1983; Veron & Hawkins 1995; or more recently Brunzendorf & Meusinger 2002; Rengstorf et al. 2004). Several gravitational microlensing survey groups have been monitoring hundreds of millions of stars toward dense regions such as the Galactic Centre, the Galactic disc and/or the Magellanic Clouds (EROS: Derue et al. 1999; MACHO: Alcock et al. 2000; MOA: Bond et al. 2001, OGLE: Udalski et al. 2003). Eyer (2002) searched QSO candidates towards the Magellanic Clouds via variability by using the second phase of the OGLE experiment[1] (OGLE-II; Udalski, Kubiak & Szymański 1997) variable star catalogue (Żebruń et al. 2001). Dobrzycki et al. (2003) did follow-up spectroscopic observations of 12 of these quasar candidates in the Small Magellanic Cloud fields and confirmed five as QSOs. They also found the colour information is useful to select QSOs. Geha et al. (2003) found about 47 QSOs behind the Magellanic Clouds, by selecting the candidates via variability in the MACHO data base and follow-up spectroscopic observations.

In this work, following Eyer (2002), we search for QSO candidates via variability in OGLE-II Galactic bulge fields (Udalski et al. 2002). Up to now, no QSOs have been found in these regions. The main motivation for this study is that quasars may provide

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[1] See http://www.astrouw.edu.pl/∼ogle or http://bulge.princeton.edu/∼ogle

background sources that fix the astrometric reference frame. Kinematic studies of stars (Sumi, Eyer & Wozniak 2003; Sumi et al. 2004) would greatly benefit from having absolute astrometry. These QSOs will also be useful for the future astrometric program, such as Space Interferometry Mission (SIM) and GAIA. However, finding QSOs in these fields is more challenging than in Magellanic Cloud fields because of the higher stellar density and higher extinction.

In Section 2 we describe the data. We select QSO candidates in Section 3. Discussion and conclusion are given in Section 4.

2 DATA

We use the *VI* photometric maps of OGLE-II fields (Udalski et al. 2002), which contain *VI* photometry and astrometry of ∼30 million stars in the 49 Galactic bulge fields. Positions of these fields (BUL_SC1 ∼ 49) can be found in Udalski et al. (2002). We do not use BUL_SC44 in this work because its extinction is too high ($A_V > 4$). The photometry is the mean photometry from a few hundred measurements in the *I* and and several measurements in the *V* band collected between 1997 and 2000. Accuracy of the zero points of the photometry is about 0.04 mag. A single 2048 × 8192 pixel frame covers an area of 0.24 × 0.95 $\deg^2$ with a pixel size of 0.417 arcsec. Details of the instrumentation set-up can be found in Udalski et al. (1997).

We also use the light curves of objects in the OGLE-II Galactic bulge variable star catalogue (Woźniak et al. 2002), which contain 213 965 variable objects. The variable object detection and the photometry have been done by using the Difference Image Analysis (DIA) of Alard & Lupton (1998), Alard (2000) and Woźniak (2000) for the data collected during the first 3 yr of the OGLE-II project. We extended the light curves to the fourth year (2000) using the method of Woźniak et al. (2002); however, new variable object detection is not attempted for the additional data.

3 QSO CANDIDATES SELECTION

We cross-referenced 213 965 variable objects in the variable star catalogue (Woźniak et al. 2002) with objects in OGLE-II photometric maps (Udalski et al. 2002), which are well calibrated, and extracted their *V* and *I* magnitudes. 205 473 of them have counterparts in the photometric maps. We use these magnitudes in the following analysis.

We chose 30 219 objects fainter than $I_0 = 16$ mag, where I_0 is the *I*-band magnitude after extinctions are corrected by using the extinction map in these fields (Sumi 2004). We show the colour–magnitude diagram (CMD) of one of these fields in Fig. 1. The detection limit in the variable star catalogue is about $I = 19.5$ mag, which corresponds to extinction-corrected magnitudes of 17 ∼ 18.5 $< I_0$, depending on the level of extinction in each field. The number density of QSOs brighter than $i = 19.1$ mag is 9.6 $\deg^{-2}$ (Vanden Berk et al. 2004), where the Sloan *i* is almost similar to the OGLE *I*. So in this magnitude range we expect 20 ∼ 30 QSOs in our 48 fields covering ∼11 square degrees taking the extinction into account.

There are many artifacts in the variable star catalogue. The light curves of objects around bright stars are affected by the long wings of the Point Spread Function (PSF) of that bright star, and then they resemble that star's variability. Even around a star with constant brightness, the wings can affect nearby faint stars owing to variations of seeing and the PSF. This effect causes the systematic gap in the brightness of faint stars around a bright star between 1998 and 1999 due to the re-aluminization of the mirror, which changed the size and/or shape of the PSF. Such light curves with a systematic gap are one of the major contaminations in our QSO selection. So we masked the stars, around the bright stars including saturated stars. Saturated stars are not in the star catalogue. To deal with them we counted the number of continuous pixels, $N_{\rm sat}$, whose ADU value is larger than 12 000 on the OGLE-II template image. Then we masked the area centred at these pixels with a radius of $4 + 5 \times \sqrt{N_{\rm sat}}$. This removed 62 per cent of variable stars though only 11 per cent of the area in total is masked. At this point, 11 535 light curves still remain.

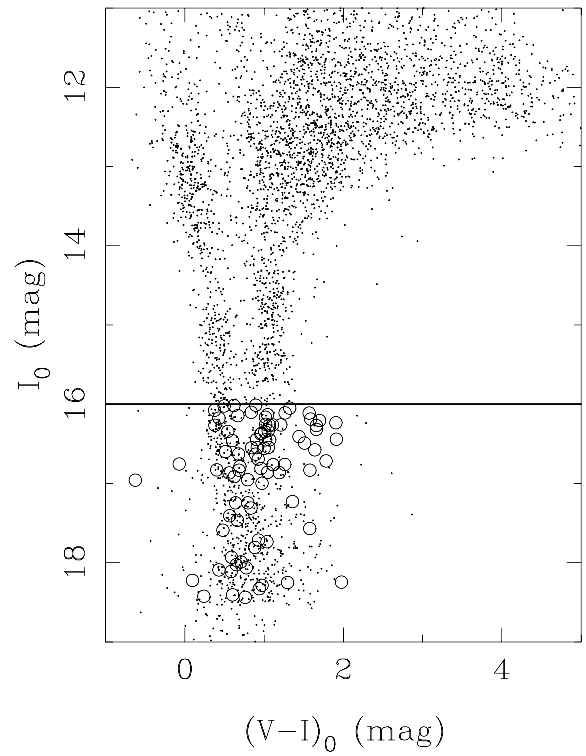

Figure 1. Extinction-corrected colour–magnitude diagram of variable stars in BUL_SC1 (dots) and QSO candidates in all fields (open circles). Candidates are searched for $I_0 < 16$.

Following Eyer (2002), we use the variogram/structure function (Hughes, Aller, & Aller 1992; Eyer & Genton 1999) to find objects with increasing variability on longer time-scales. We measure the slope of the variogram as follows. For all possible pairs of measurements, differences of times $h_{i,j} = t_j - t_i$ and squares of difference of magnitudes $(I_j - I_i)^2$ are computed. For a given bin of $\log h$, the median of $(I_j - I_i)^2$ is estimated, and is noted as Var(h). This gives a spread of the variation of *I* in this time-scale. We bin $\log h$ for three parts divided by 1.5, 2, 2.5, 3, then measure the slope, $S_{\rm var} = {\rm d\,Var}(h)/{\rm d} \log h$. The larger $S_{\rm var}$, the larger the variability on larger time-scales. We reject light curves with $S_{\rm var} < 0.09$, which is a slightly more conservative value than the 0.1 used in Eyer (2002). We search for periodicity in the light curves by using the AoV algorithm (Schwarzenberg-Czerny 1989). Then we reject the light curves in which strong periodicity is detected with AoV periodograms larger than 50. This value was chosen empirically. We show two sample light curves and Var(h) as a function of $\log h$ in Fig. 2. After this procedure, 3201 light curves remain.

The remaining light curves were inspected by eye. First we reject apparent periodic and semi-periodic variables that couldn't be rejected by the previous procedure. After this, 500 light curves are left.

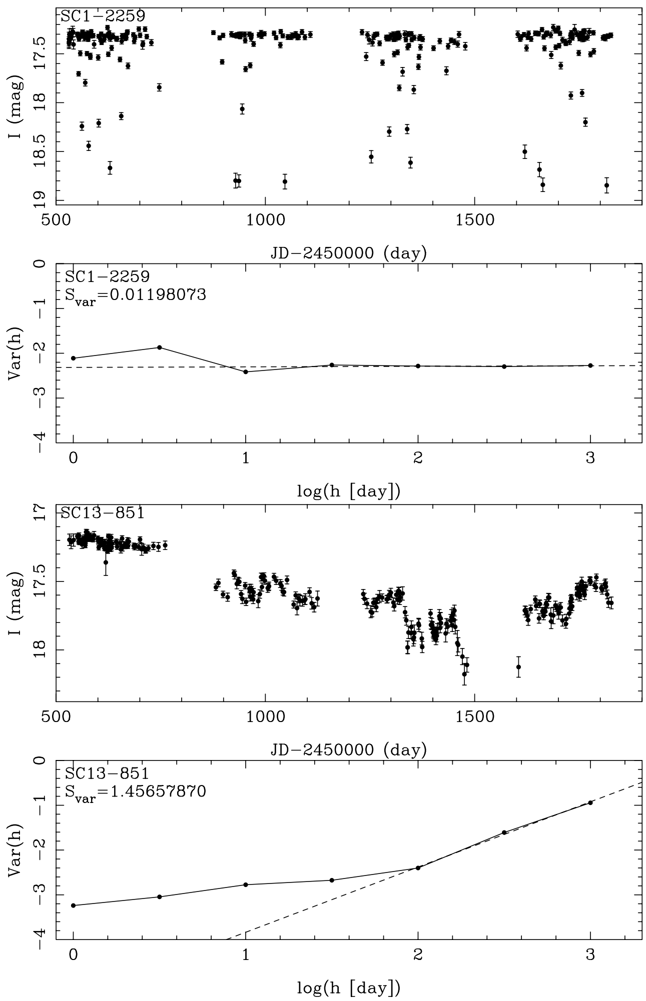

Figure 2. Sample light curves (first and third panel) and variogram/structure function Var(h) as a function of log h (second and fourth panel, dot with solid line) for objects that passed the mask around bright stars. The top two and bottom two panels are objects that failed (sc1-2259) and passed (sc13-851) the criteria, $S_{\rm var} \geqslant 0.09$ and AoV algorithm <50. In the second and fourth panels, dashed lines represent the best fit for the three points (log $h = 2$, 2.5, 3) whose slopes $S_{\rm var}$ are written in the panels.

The main contamination after this selection are high proper motion objects and artifacts around bright variable stars. We reject them as follows.

When an object moves from the position at the template image, DIA produces a pair of positive and negative residuals on the subtracted image. The flux of these residuals increases as a function of the displacement of positions of the objects (Eyer & Woźniak 2001; Soszynski et al. 2002). We cross-refer with the proper motion catalogue (Sumi et al. 2004) to check if they have high proper motion or if there is a high proper motion object nearby. Even if its proper motion is not so high, a bright nearby star can produce a pair of significant residuals and constantly increase or decrease the brightness of the nearby faint stars. To reject them, we look at the light curves of all neighbouring stars in OGLE-II photometric maps within 20 pixels around the object, which were made using DIA. Then we check whether they have a companion with an opposite (increasing or decreasing brightness) light curve around them.

In this process, we also reject the light curves that have neighbours with similar light curves. Usually they are affected by nearby bright variable stars but were not masked and not clearly identified in previous procedures because the shape of their light curves are distorted from the original variable owing to the combination of the other artifacts or low S/N. The combination of the effect of the variable star and the high proper motion object resemble the QSO light curve.

Table 1. The number of remaining candidates after each selection criterion.

Criteria	Candidates
All variable objects	213 965
Faint (Extinction corrected I, $I_0 > 16$ mag)	30 219
Mask around bright stars	11 535
$S_{\rm var} \geqslant 0.09$ and AoV periodogram <50	3 201
Eye inspection 1, cut apparent periodic variables	500
Eye inspection 2, cut high proper motion objects	97

Finally we have 97 QSO candidates. We summarize our selection criteria and the number of remaining candidates after each selection criterion in Table 1. We show 20 sample light curves in Fig. 3 and list them in Table 2, where the objects with $V{-}I = (V{-}I)_0 = 9.999$ don't have V-band photometry. The complete list and light curves of all 97 candidates are available in electronic format at http://www.astro.princeton.edu/ sumi/QSO-OGLEII/. We also show their position on the CMD as open circles in Fig. 1.

As we can see in Fig. 1, many of our candidates are relatively bright ($I_0 = 16 \sim 17$), which is not expected from a genuine quasar Luminosity Function. This means the contamination by irregular variable stars is higher in this range than expected. In this work we didn't put any cut by their colour, for the following reasons. For blue objects, there are only few candidates with $(V{-}I)_0 < 0.4$ (Dobrzycki et al. 2003). The Be stars, which were a major contamination in the previous work (Eyer 2002), are above the threshold brightness $I_0 < 16$ mag. For the redder objects, the extinction may be underestimated for background objects because the extinctions are estimated only up to the Galactic Centre in Sumi (2004). Some objects don't have V photometry.

4 DISCUSSION AND CONCLUSION

We have selected 97 QSO candidates via variability from OGLE-II DIA variable star catalogue in the Galactic bulge fields.

Finding the QSOs in such crowded and high extinction fields is challenging, but should be useful for the astrometric zero-point in these fields and for the study of the foreground dust. It is especially useful for the study of the bar structure by using the stellar proper motions in these fields (Sumi et al. 2004). These QSOs will also be useful for future astrometric programmes, such as the Space Interferometry Mission (SIM) and GAIA.

Spectroscopic follow-up observations are required to confirm these QSOs. Multi-object and wide-field spectrographs, such as VIMOS/VLT and LDSS/Magellan, are suitable for this purpose. We are planning to carry out spectroscopic follow-up observations in four of these fields (BUL_SC1, 2, 32 and 45) by using VIMOS/VLT. Follow-up observations in other fields are strongly encouraged.

As we can see in Fig. 1, there are more candidates at relatively bright ($I_0 = 16 \sim 17$) range, which is not expected from a genuine quasar Luminosity Function. This means the contamination by irregular variable stars is higher in this range than the fainter range. So, the efficiency would be higher in these fainter ($I_0 > 17$) candidates. There are several objects that may be microlensing events, i.e. SC2-3191, SC2-4502, SC14-4009, SC19-4350, SC24-3042,

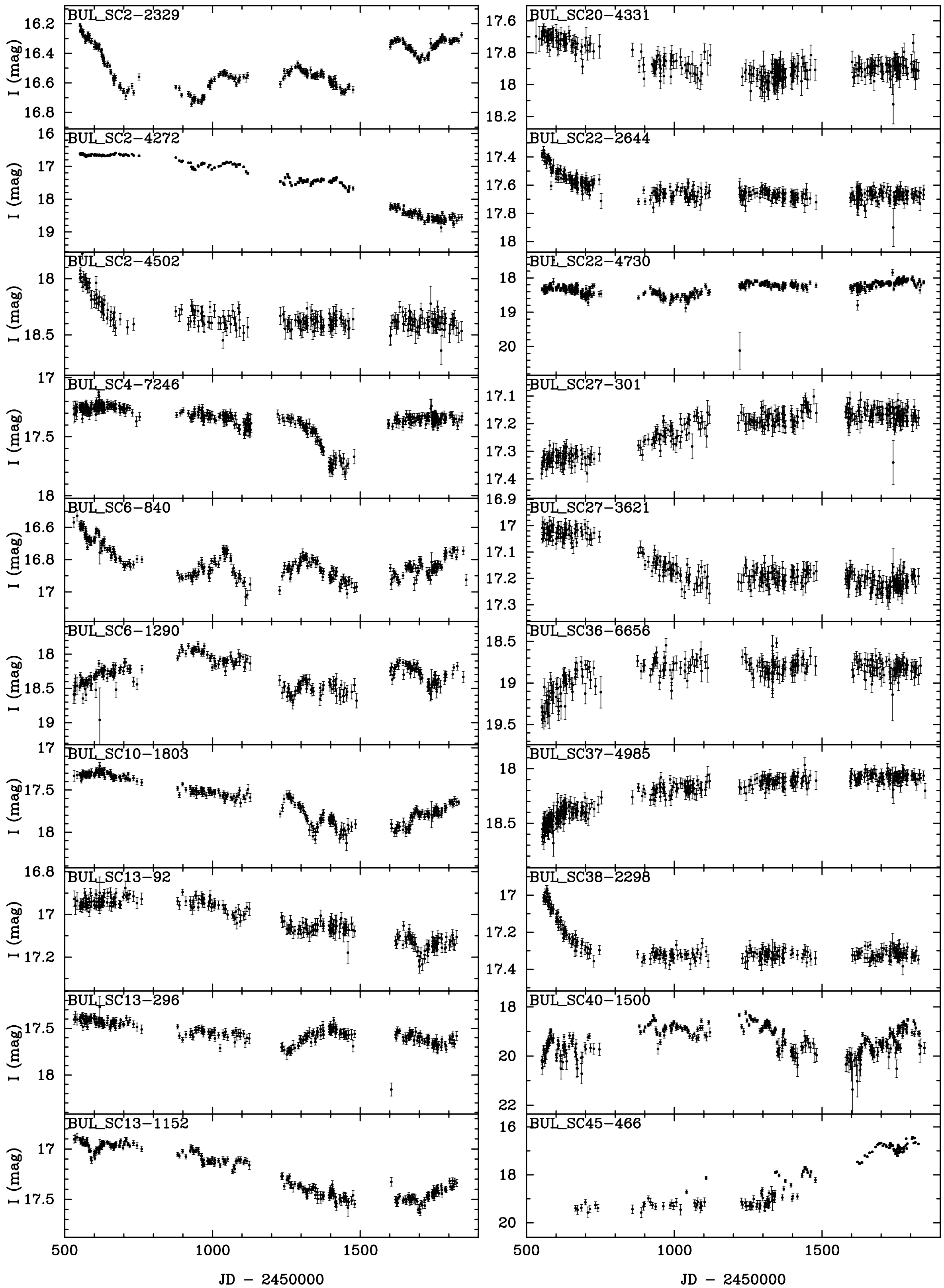

Figure 3. 20 sample *I*-band light curves in 97 QSO candidates. The light curves of all 97 candidates are available in electronic format at http://www.astro.princeton.edu/∼sumi/QSO-OGLEII/.

SC30-3977, SC38-2298 and SC39-5030. We retained these objects because we do not know whether they are true microlensing or not. Also there are several objects that have light curves too similar to each other to be QSOs, i.e. SC4-7246, SC13-332, SC13-775, SC20-3616, SC32-1795 SC42-3375, SC42-3772 and SC46-742. They have relatively constant baseline with W- or V-shaped dents in their light curves. They could be new a type of variable star. We did not reject them because we do not know what they are.

Table 2. The list of the first 10 sample of 97 QSO candidates. The complete list of all 97 candidates is available in electronic format at http://www.astro.princeton.edu/~sumi/QSO-OGLEII/. Columns are field number, identification number as in Woźniak et al. (2001), $\mathrm{ID_v}$, and as in Udalski et al. (2002), ID, Positions on CCD in pixel, x and y, Equatorial coordinates RA and Dec. in equinox 2000, I-band magnitude and colour, I, V–I and extinction corrected magnitude and colour, I_0, $(V–I)_0$, Variogram slope, S_{var}. The objects with $V-I = (V-I)_0 = 9.999$ don't have V-band photometry.

Field	$\mathrm{ID_v}$	ID	x (pixel)	y (pixel)	RA(2000)	Dec.(2000)	I	V–I	I_0	$(V–I)_0$	S_{var}
BUL_SC1	2411	468485	1350.47	4479.39	$18^h02^m42\overset{s}{.}91$	$-29^h55^m02\overset{s}{.}7$	18.828	1.195	18.091	0.431	0.19
BUL_SC2	2329	304696	937.12	3632.55	$18^h04^m25\overset{s}{.}85$	$-28^h55^m46\overset{s}{.}9$	17.118	2.614	16.441	1.912	0.94
BUL_SC2	2423	506014	1282.18	3824.72	$18^h04^m36\overset{s}{.}73$	$-28^h54^m27\overset{s}{.}5$	17.416	1.789	16.764	1.113	0.68
BUL_SC2	3191	337864	947.12	4930.96	$18^h04^m26\overset{s}{.}21$	$-28^h46^m49\overset{s}{.}6$	19.155	1.379	18.407	0.603	0.15
BUL_SC2	3340	136127	369.57	5145.97	$18^h04^m08\overset{s}{.}05$	$-28^h45^m20\overset{s}{.}2$	17.081	1.691	16.373	0.957	0.13
BUL_SC2	4136	165056	138.64	6347.10	$18^h04^m00\overset{s}{.}87$	$-28^h37^m03\overset{s}{.}0$	17.087	1.317	16.341	0.544	0.43
BUL_SC2	4272	164645	385.54	6631.55	$18^h04^m08\overset{s}{.}64$	$-28^h35^m05\overset{s}{.}5$	17.289	1.941	16.449	1.070	2.31
BUL_SC2	4502	775796	1942.63	6850.26	$18^h04^m57\overset{s}{.}55$	$-28^h33^m35\overset{s}{.}6$	18.521	1.625	17.806	0.883	0.25
BUL_SC4	3598	84694	129.22	3250.07	$17^h54^m07\overset{s}{.}22$	$-29^h49^m30\overset{s}{.}2$	18.059	1.793	16.868	0.558	0.27
BUL_SC4	6483	717606	1960.77	5624.77	$17^h55^m05\overset{s}{.}47$	$-29^h33^m08\overset{s}{.}2$	18.841	9.999	17.697	9.999	0.09

The current data set is not optimal for finding QSOs. The OGLE-II Galactic bulge data are relatively shallower than the OGLE-II Magellanic Cloud data, which are optimized to find microlensing events. Variable objects were only searched during the first 3 yr for some reason. We can improve the sensitivity by including the fourth year of OGLE-II and OGLE-III to increase the time-scale and the survey area.

The main contamination in this work was artifacts around bright stars or from high proper motion stars rather than Be stars as in revious work (Eyer 2002). Because the foreground stars are closer than Magellanic Clouds, most Be stars are above the threshold brightness. On the other hand, owing to much higher stellar density, the artifacts are increased.

Work to avoid such artifacts in photometry on subtracted images is underway. If such new photometry were to be done, then the efficiency of finding QSOs would be increased.

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REFERENCES

Alard C., 2000, A&AS, 144, 363
Alard C., Lupton R. H., 1998, ApJ, 503, 325
Alcock C. et al., 2000, ApJ, 541, 734
Bond I. A. et al., 2001, MNRAS, 327, 868
Brunzendorf J., Meusinger H., 2002, A&A, 390, 879
Derue F. et al., 1999, A&A, 351, 87
Dobrzycki A., Groot P. J., Macri L. M., Stanek K. Z., 2002, ApJ, 569, L15
Dobrzycki A., Macri L. M., Stanek K. Z., Groot P. J., 2003, AJ, 125, 1330
Eyer L., 2002, Acta Astron., 52, 241
Eyer L., Genton M. G., 1999, A&AS, 136, 421
Eyer L., Woźniak P. R., 2001, MNRAS, 327, 601
Geha M. et al., 2003, AJ, 125, 1
Hawkins M. R. S., 1983, MNRAS, 202, 571
Hughes P. A., Aller H. D., Aller M. F., 1992, ApJ, 396, 469
Rengstorf A. W. et al., 2004, ApJ, 606, 741
Schwarzenberg-Czerny A., 1989, MNRAS, 241, 153
Soszyński I. et al., 2002, Acta Astron., 52, 143
Sumi T., 2004, MNRAS, 349, 193
Sumi T., Eyer L., Wozniak P. R., 2003, MNRAS, 340, 1346
Sumi T. et al., 2004, MNRAS, 348, 1439
Udalski A., 2003, Acta Astron., 53, 291
Udalski A., Kubiak M., Szymański M. K., 1997, Acta Astron., 74, 319
Udalski A. et al., 2002, Acta Astron., 52, 217
Vanden Berk D. E. et al., 2004, ApJ, submitted
Veron P., Hawkins M. R. S., 1995, A&A, 296, 665
Woźniak P. R., 2000, Acta Astron., 50, 421
Woźniak P. R., Udalski A., Szymański M. K., Kubiak M., Pietrzyński G., Soszyński I., Żebruń K., 2002, Acta Astron., 52, 129
Żebruń K. et al., 2001, Acta Astron., 51, 317

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