The Optical Gravitational Lensing Experiment. Eclipsing Binary Stars in the Small Magellanic Cloud *

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ABSTRACT

We present the catalog of 1459 eclipsing binary stars detected in the central 2.4 square degree area of the Small Magellanic Cloud during the OGLE-II microlensing search. The sample includes objects brighter than $I \approx 20$ mag with periods ranging from about 0.3 to 250 days. The average completeness of the catalog is about 80%. Statistics of the entire sample and well detached systems, suitable for distance determination, are also presented.

The catalog, finding charts and BVI photometry data for all objects are available from the OGLE Internet archive.

1 Introduction

Eclipsing binary stars are among the oldest variable stars recognized and correctly interpreted by astronomers. In 1780s Pigott and Goodricke observed β Per (Algol) and explained its variability by binarity of the system in which two components obscure periodically each other. For years methods of analysis of eclipsing star light curves were developed and improved. The binary systems became one of the most important sources of information about stellar parameters like radii, masses, luminosities etc. Also theory of evolution of binary stars, in particular close systems exchanging mass during

*Based on observations obtained with the 1.3 m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution of Washington.

evolution, was developed during the past decades. Thus, eclipsing systems seem to be a group which is well understood, although somewhat off the main astrophysical interest.

However, eclipsing binary stars might once again become one of the most important objects in the near Universe. They seem to be the most promising candidates for standard candles allowing determination of distances within the Local Group with so far unprecedented accuracy of a few percent (Paczyński 1997).

The principle of the method was first recognized by Stebbins (1910). With accurate photometry and spectroscopy absolute dimensions of both components can precisely be derived and, together with accurately determined temperatures, *i.e.*, surface brightness of each component, emitted fluxes can be calculated. This should give precise distance when compared with the flux observed at the Earth. The method is essentially geometric, free from possible population effects influencing other standard candles. The parameters of components should be determined with high precision, therefore only well detached systems should be used. A few percent accuracy of distance determination should be achieved when good quality observations are available.

Eclipsing binaries are very common but difficult to detect because very good sampling of the light curve is necessary to detect eclipses. Fortunately large samples of these objects emerge as by-products of microlensing searches, *e.g.*, in the Large Magellanic Cloud (Grison *et al.* 1994, Alcock *et al.* 1997) or Galactic bulge (Udalski *et al.* 1997a). Several eclipsing binaries in M31 and M33 have recently been discovered by DIRECT project searching for eclipsing systems in these galaxies (Kaluzny *et al.* 1998, Stanek *et al.* 1998).

First successful application of the eclipsing binary for distance determination to the LMC was already presented with HV2274 system (Guinan *et al.* 1998, Udalski *et al.* 1998b). Results of these studies seem to confirm shorter distance scale to the LMC, $(m-M)_{\rm LMC} \approx 18.2-18.3$ mag, than generally accepted value of $(m-M)_{\rm LMC} \approx 18.5$ mag making an important step toward ending the long lasting dispute on the LMC distance. The distance to the LMC is crucial for modern astrophysics, as the extragalactic distance scale is tied to the LMC distance. We believe that eclipsing binaries will provide accurate absolute distances to many objects within the Local Group enabling precise calibration of other standard candles.

This paper is aimed at providing a list and photometry of eclipsing binaries detected during the OGLE-II microlensing search (Udalski, Kubiak and

Szymański 1997b) in the Small Magellanic Cloud. The catalog of eclipsing binaries contains 1459 objects with full variety of eclipsing systems. The sample is reasonably complete, allowing statistical analysis. It should provide a good material for testing theory of evolution of binary systems as well as studying the SMC evolution, star formation etc.

Many of the eclipsing systems presented in this paper are well detached systems well suited for distance determination. With the largest 6–8 m class telescopes being currently constructed in the southern hemisphere, it should be possible to obtain high resolution spectra of all these, even quite faint, objects. Eclipsing binaries should then provide not only precise mean distance to the SMC but, also, should allow to study geometry and spatial distribution of stars in the SMC.

2 Observations

All observations presented in this paper were carried out with the 1.3-m Warsaw telescope at the Las Campanas Observatory, Chile, which is operated by the Carnegie Institution of Washington, during the second phase of the OGLE experiment. The telescope was equipped with the "first generation" camera with a SITe 2048×2048 CCD detector. The pixel size was 24 μm giving the 0.417 arcsec/pixel scale. Observations of the SMC were performed in the "slow" reading mode of the CCD detector with the gain 3.8 e^-/ADU and readout noise about 5.4 e^-. Details of the instrumentation setup can be found in Udalski, Kubiak and Szymański (1997b).

Observations of the SMC started on June 26, 1997. As the microlensing search is planned to last for a few years, observations of selected fields will be continued during following seasons. In this paper we present data collected up to November 27, 1998. Observations are obtained in the standard *BVI*-bands with majority of measurements made in the *I*-band.

Photometric data collected in the course of the first observing season of the SMC for 11 fields (SMC_SC1–SMC_SC11) covered about 2.4 square degree of the central parts of the SMC and were used to construct the *BVI* maps of the SMC (Udalski *et al.* 1998a). The reader is referred to that paper for more details about methods of data reduction, tests on quality of photometric data, astrometry etc.

3 Search for Eclipsing Binary Stars

Search for variable objects in 11 SMC fields (Table 1) was performed using observations in the I-band in which majority of observations was obtained. Typically about 140–180 epochs were available for each analyzed object with the lower limit set to 50. The mean I-band magnitude of objects was limited to $I < 20$ mag. Candidates for variable stars were selected based on comparison of the standard deviation of all individual measurements of a star with typical standard deviation for stars of similar brightness. Light curves of selected candidates were then searched for periodicity using the AoV algorithm (Schwarzenberg-Czerny 1989) which was successfully applied in earlier, OGLE-I variable stars searches (*e.g.*, Udalski *et al.* 1997a). The period search was limited to the range 0.1–100 days. However, a few objects were identified with $P/2$ period and their true period exceeds that upper limit.

Table 1

Equatorial coordinates of the SMC fields

Field	RA (J2000)	DEC (J2000)
SMC_SC1	$0^h37^m51^s$	$-73°29'40''$
SMC_SC2	$0^h40^m53^s$	$-73°17'30''$
SMC_SC3	$0^h43^m58^s$	$-73°12'30''$
SMC_SC4	$0^h46^m59^s$	$-73°07'30''$
SMC_SC5	$0^h50^m01^s$	$-73°08'45''$
SMC_SC6	$0^h53^m01^s$	$-72°58'40''$
SMC_SC7	$0^h56^m00^s$	$-72°53'35''$
SMC_SC8	$0^h58^m58^s$	$-72°39'30''$
SMC_SC9	$1^h01^m55^s$	$-72°32'35''$
SMC_SC10	$1^h04^m51^s$	$-72°24'45''$
SMC_SC11	$1^h07^m45^s$	$-72°39'30''$

Light curves of all objects revealing statistically significant periodic signal were then displayed and visually inspected to avoid spurious detections. Eclipsing binaries were extracted from the entire sample when their light curve displayed either evident narrow eclipses or round shape light curve with wide eclipses of different depth or with sharp minima. This should reject ellipsoidal variable stars with sinusoidal light curves from our sample of eclipsing systems. Although the ellipsoidal stars variability is caused by similar reasons to eclipsing stars – orbital motion of components, they can easily be confused with variable stars of other types which would make our sample inhomogeneous.

In the next step periods of selected eclipsing star candidates were tuned to smooth the eclipse shape which is very sensitive to period inaccuracies. Then brightness of each object outside the eclipse was determined. To derive colors, observations in the B and V-bands which are less numerous than in the I-band were first folded with the system period and then brightness outside eclipse was determined. Accuracy of colors is about 0.03 mag and 0.02 mag for $B-V$ and $V-I$, respectively. Accuracy of period is equal to about $1\times10^{-4}P$.

Each of the analyzed SMC fields overlaps with neighboring fields for calibration purposes. Therefore several eclipsing stars located in the overlapping regions were detected twice. We decided not to remove them from the final list of objects because their measurements are independent in both fields. 68 such stars were detected and we provide cross-reference list to identify them.

4 Catalog of Eclipsing Binary Stars

Eclipsing binary stars detected by OGLE-II in the SMC fields are listed in Tables 2–12. They contain the identification number in the field database, equatorial coordinates (J2000), period in days, zero epoch corresponding to the deeper eclipse, I-band magnitude and $B-V$ and $V-I$ colors. Photometry corresponds to the maximum of brightness.

All tables contain 1527 stars. 68 of them were identified twice in overlapping regions between neighboring fields. Table 13 provides cross-reference list to identify these objects.

Appendices A–K present I-band light curves of all objects included in the catalog. The ordinate is phase with 0.0 value corresponding to the deeper eclipse. Abscissa is I-band magnitude. Light curve is repeated twice for clarity.

Finding charts are not presented in this paper but they are available from the OGLE Internet archive (see below).

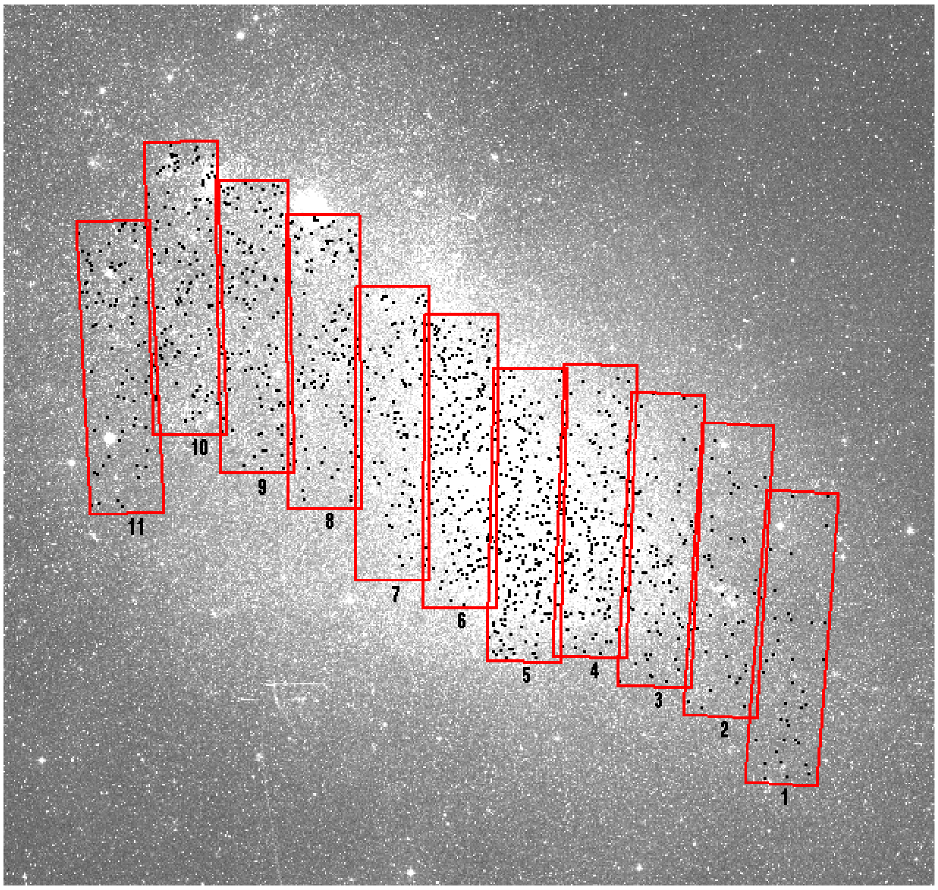

Fig. 1. OGLE-II fields in the SMC. Black dots indicate positions of eclipsing stars. North is up and East to the left.

5 Discussion

We present 1459 eclipsing stars located in the central regions of the SMC. Although we did not attempt to identify presented stars with previously known from photographic observations we suspect that the vast majority of these objects are newly discovered eclipsing systems. The sample contains a wide range of eclipsing objects – from well detached Algol systems, through semi-detached objects to β Lyrae stars. Many systems reveal eccentric orbits with possible apsidal motion. Some of the objects, in particular those with the longest periods, might have been misclassified because few cycles were covered during the presented period of observations. For example, we included in the catalog a strange object, OGLE SMC_SC5 208025, which displays eclipse-like features in the light curve superimposed on other variability.

Quality of photometry varies from object to object mostly depending on brightness of the star and also on crowding of the field. For many stars quality of light curve is sufficient for any application including distance determination. For fainter objects more precise data might be necessary. However, knowing the ephemeris of such star one can optimize additional observations.

Fig. 1 presents the picture of the SMC from the Digitized Sky Survey CD-ROMs with contours of the OGLE-II fields. Positions of the eclipsing binaries are marked with black dots. The stars are distributed more or less proportionally to the stellar density with the largest concentration in the fields SMC_SC4–SMC_SC6, *i.e.*, at the SMC center.

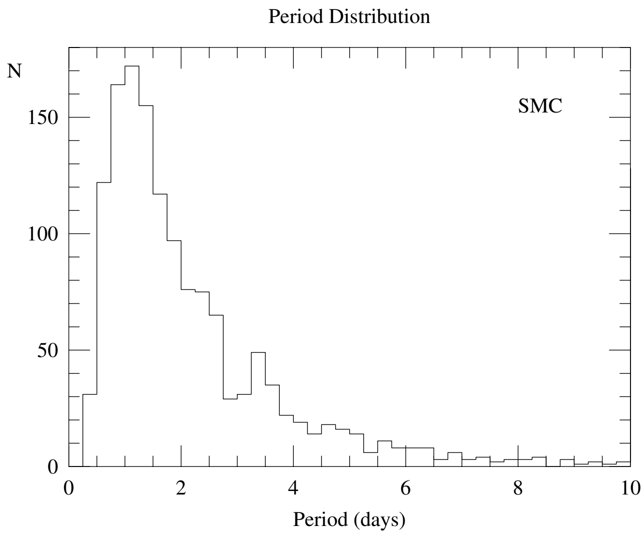

Fig. 2. Histogram of orbital periods of eclipsing binaries in 0.25 day bins. Additional 128 objects have periods longer than 10 days.

Fig. 2 shows the histogram of orbital periods of all stars from the catalog in 0.25 day bins from 0.0 to 10 days. Additional 128 objects with periods above 10 days are distributed more or less uniformly. As one can expect, the majority of stars are short period eclipsing systems with the typical orbital period around 1.1 day. The number of systems falls rapidly with increasing period.

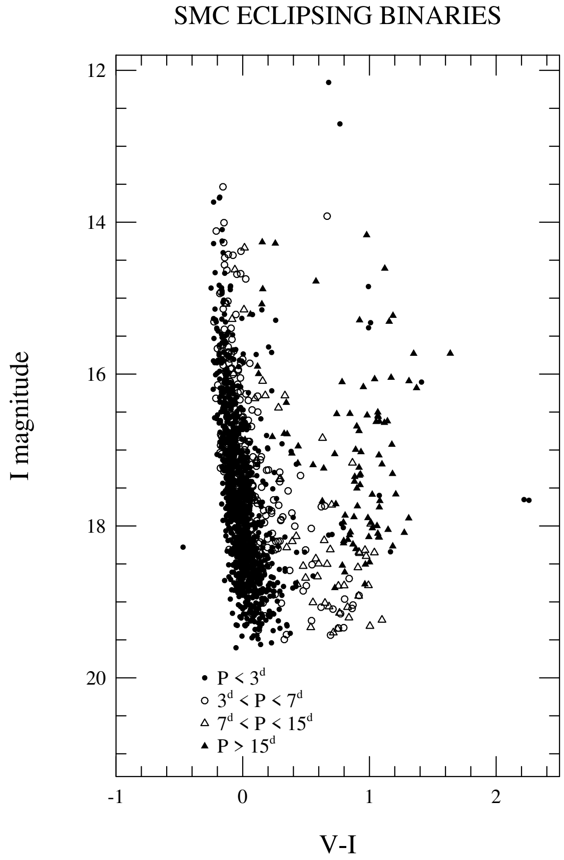

Fig. 3. Color-magnitude diagram of eclipsing stars in the SMC. Different symbols mark positions of stars with short, medium, long and very-long periods.

Fig. 3 presents I *vs.* $V-I$ color-magnitude diagram for all stars from the catalog. Different symbols mark short $(P<3^{\rm d})$, medium $(3^{\rm d}<P<7^{\rm d})$, long $(7^{\rm d}<P<15^{\rm d})$ and very-long $(P>15^{\rm d})$ period systems. Fig. 3 indicates that practically all eclipsing systems from the catalog belong to the SMC. There are very few foreground systems. Eclipsing systems with short and medium periods belong to the young population located in the main sequence. Long period stars are usually lower giant branch stars or evolved main sequence stars while very-long period stars populate upper part of the red giant branch. The number of giant branch eclipsing systems is much smaller than shorter period stars because such wide systems are much more rare. Inclination of orbit of those stars must be much closer to 90 deg than for close binary systems. Also, the efficiency of detection for very-long period systems is certainly lower due to smaller number of cycles covered.

Figs. 1–3 indicate that the eclipsing stars from the catalog constitute in many respects a very representative sample of stars from the SMC. The question is how complete is this sample. In general, the completeness is a function of magnitude, quality of photometry, period etc. We attempted to determine the mean completeness of our catalog based on objects detected in overlapping regions of neighboring fields. Based on astrometric solutions for each field we selected eclipsing stars which should be detected in neighboring fields and compared these objects with actually detected stars. 20 such tests were possible between our 11 fields. 170 stars should be theoretically paired up. In practice 136 pairs were found, yielding the mean completeness of our catalog equal to 80%. It should be noted that this is certainly a lower limit as the edge regions of each field are affected by non-perfect pointing of the telescope leading to effectively smaller number of observations there.

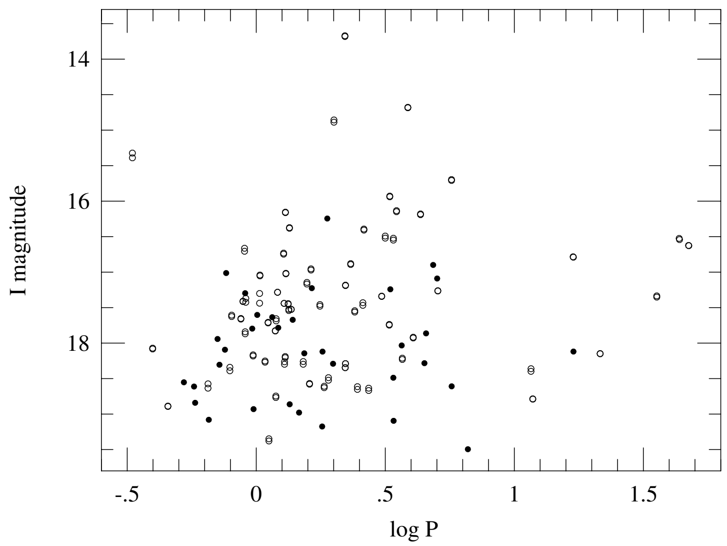

Fig. 4. Brightness *vs.* $\log P$ diagram for eclipsing stars which should be paired up with stars located in neighboring fields. Open circles mark identified stars while filled circles those which remained unpaired.

Fig. 4 presents the diagram of brightness of the system *vs.* $\log P$ for stars used in our tests. Open circles mark objects which were identified in neigh-

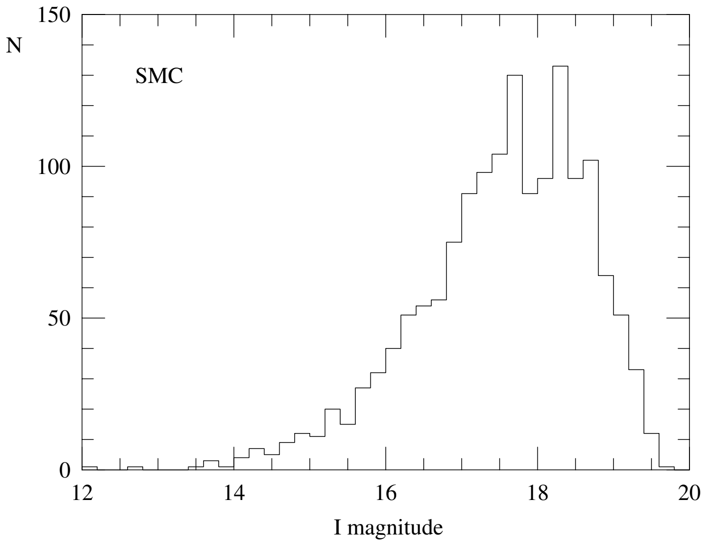

Fig. 5. Histogram of brightness of eclipsing stars in 0.2 mag bins.

boring fields. Filled circles show missed pairs. It is clear that completeness is a function of magnitude and most unpaired stars are objects fainter than $I \approx 18$ mag. Fig. 5 presents the histogram of brightness of all eclipsing binaries. Figs. 4 and 5 indicate that completeness is likely to be better than 90% for objects brighter than $I < 17.5$ mag and it falls gradually to zero for stars fainter than $I \approx 19.5$ mag.

One of the most direct and important applications of the catalog is selection of systems suitable for distance determination. The catalog contains many well detached eclipsing systems which, when precise spectroscopy is available, should provide accurate distances. The best systems for distance determination should possess deep and narrow eclipses assuring that both components are spherical and well separated. To facilitate selection we extracted from the catalog 153 object sample of detached eclipsing systems with well defined eclipses of similar depth (depth of the secondary – shallower – eclipse larger than half of the primary one), possibly flat light curve between eclipses and good photometry. In Fig. 6 we plot depth of the secondary eclipse as a function of full width at half depth of the secondary eclipse measured as fraction of the orbital period. It can be seen from Fig. 6 that the typical width of the secondary eclipse is about $0.06 - 0.07P$ with depth 0.3–0.5 mag. The deepest secondary eclipse systems include SMC_SC5 283079, SMC_SC2 11454 and SMC_SC6 251588 with depth about $0.65 - 0.7$ mag.

One should remember that depth for two identical star system with total eclipses would be 0.75 mag. The most narrow eclipses are those of SMC_SC6 242498, SMC_SC5 180516, SMC_SC4 192903 ($P = 103$ days), SMC_SC6 11143 and SMC_SC4 14924 – all below $0.03P$. The list of all selected detached systems is available from the OGLE Internet archive.

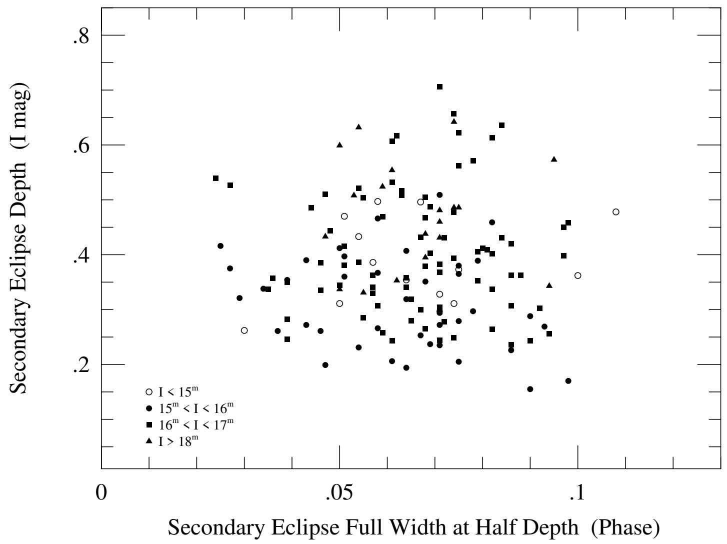

Fig. 6. Depth *vs.* full width at half depth of the secondary eclipse of well detached eclipsing systems.

Summarizing, we provide a reasonably complete sample of eclipsing binary stars from the SMC. It can be used for statistical analysis of the SMC stars and many other projects requiring multiband photometry of eclipsing stars. Similar catalog of eclipsing systems in the LMC will be released by the OGLE-II collaboration in the near future.

The catalog, including BVI-band photometry data and finding charts is available to the astronomical community from the OGLE archive:
http://www.astrouw.edu.pl/˜ftp/ogle or its mirror
http://www.astro.princeton.edu/˜ogle

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T a b l e 13

Cross-identification of stars detected in overlapping regions

SMC_SC1	97290	↔	SMC_SC2	2742
SMC_SC1	108856	↔	SMC_SC2	10301
SMC_SC2	86546	↔	SMC_SC3	8986
SMC_SC2	88691	↔	SMC_SC3	13032
SMC_SC3	193416	↔	SMC_SC4	8326
SMC_SC3	194000	↔	SMC_SC4	8987
SMC_SC3	198240	↔	SMC_SC4	11552
SMC_SC3	202981	↔	SMC_SC4	15096
SMC_SC3	208373	↔	SMC_SC4	22592
SMC_SC3	213289	↔	SMC_SC4	26278
SMC_SC3	213548	↔	SMC_SC4	26565
SMC_SC3	217692	↔	SMC_SC4	29281
SMC_SC3	218379	↔	SMC_SC4	29615
SMC_SC3	222224	↔	SMC_SC4	29960
SMC_SC4	147702	↔	SMC_SC5	3407
SMC_SC4	154601	↔	SMC_SC5	12201
SMC_SC4	160383	↔	SMC_SC5	17284
SMC_SC4	163681	↔	SMC_SC5	21245
SMC_SC4	167321	↔	SMC_SC5	26819
SMC_SC4	171629	↔	SMC_SC5	38169
SMC_SC4	175149	↔	SMC_SC5	38079
SMC_SC4	175576	↔	SMC_SC5	39026
SMC_SC4	176156	↔	SMC_SC5	44249
SMC_SC4	187310	↔	SMC_SC5	61542
SMC_SC4	198836	↔	SMC_SC5	74923
SMC_SC5	255984	↔	SMC_SC6	5337
SMC_SC5	257236	↔	SMC_SC6	6812
SMC_SC5	261267	↔	SMC_SC6	11806
SMC_SC5	265970	↔	SMC_SC6	17345
SMC_SC5	266131	↔	SMC_SC6	22883
SMC_SC5	271839	↔	SMC_SC6	29314
SMC_SC5	277666	↔	SMC_SC6	29828
SMC_SC5	283889	↔	SMC_SC6	36041
SMC_SC5	300752	↔	SMC_SC6	55836
SMC_SC5	300848	↔	SMC_SC6	56181
SMC_SC5	300727	↔	SMC_SC6	61509
SMC_SC5	311566	↔	SMC_SC6	67289
SMC_SC5	311654	↔	SMC_SC6	67392
SMC_SC6	263814	↔	SMC_SC7	540
SMC_SC6	268972	↔	SMC_SC7	9072
SMC_SC6	272453	↔	SMC_SC7	13487
SMC_SC6	277060	↔	SMC_SC7	18332
SMC_SC6	292086	↔	SMC_SC7	32419
SMC_SC6	311434	↔	SMC_SC7	47309
SMC_SC6	307537	↔	SMC_SC7	47996
SMC_SC6	319956	↔	SMC_SC7	61679
SMC_SC7	233103	↔	SMC_SC8	7991
SMC_SC7	236364	↔	SMC_SC8	11553
SMC_SC7	237128	↔	SMC_SC8	15581
SMC_SC7	247769	↔	SMC_SC8	22435
SMC_SC7	255621	↔	SMC_SC8	30634
SMC_SC7	255665	↔	SMC_SC8	30691
SMC_SC7	259593	↔	SMC_SC8	35214
SMC_SC7	263170	↔	SMC_SC8	38913
SMC_SC8	170230	↔	SMC_SC9	99
SMC_SC8	174197	↔	SMC_SC9	4030
SMC_SC8	174291	↔	SMC_SC9	4108
SMC_SC8	198652	↔	SMC_SC9	30310
SMC_SC8	198995	↔	SMC_SC9	30455
SMC_SC8	207567	↔	SMC_SC9	39127
SMC_SC8	207699	↔	SMC_SC9	39292
SMC_SC9	144175	↔	SMC_SC10	114
SMC_SC9	147421	↔	SMC_SC10	6388
SMC_SC9	152769	↔	SMC_SC10	11958
SMC_SC9	161377	↔	SMC_SC10	19778
SMC_SC9	175323	↔	SMC_SC10	33878
SMC_SC9	175488	↔	SMC_SC10	33982
SMC_SC10	118942	↔	SMC_SC11	13386