Luminosity function of contact binaries based on the ASAS survey

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ABSTRACT

The luminosity function for contact binary stars of the W UMa-type is evaluated on the basis of the ASAS photometric project covering all stars south of $\delta = +28^\circ$ within a magnitude range $8 < V < 13$. Lack of colour indices enforced a limitation to 3373 systems with $P < 0.562$ days (i.e. 73% of all systems with $P < 1$ day) where a simplified $M_V(\log P)$ calibration could be used. The spatial density relative to the main sequence FGK stars of 0.2%, as established previously from the Hipparcos sample to $V = 7.5$, is confirmed. While the numbers of contact binaries in the ASAS survey are large and thus the statistical uncertainties small, derivation of the luminosity function required a correction for missed systems with small amplitudes and with orbital periods longer than 0.562 days; the correction, by a factor of $3 \times$, carries an uncertainty of about 30%.

Key words: stars: eclipsing – stars: binary – stars: evolution

1 INTRODUCTION

ASAS – All Sky Automated Survey1, is a long term project dedicated to detection and monitoring variability of bright stars using small telescopes. Recently Paczyński et al. (2006) presented results of the $V$-filter observations obtained at the Las Campanas Observatory with a single 7 cm telescope. More than 50 thousand variables brighter than 14 magnitude were discovered in about three fourth of the sky with $\delta < +28^\circ$, among them 5,384 contact binary stars.

This paper addresses the matter of the spatial density of contact binaries of the W UMa type ($P < 1$ day, from now on called “EW”) as indicated by the ASAS survey data within its magnitude limits of $8 < V < 13$. The relative spatial density (in relation to the main sequence FGK dwarfs) is evaluated via the luminosity function for the absolute magnitude range $1.5 < M_V < 5.5$.

We are very far from having a volume limited sample of EW binaries. In fact, the main problem is the completeness to a given magnitude limit. At present, the only sample which appears to include all EW binaries with photometric variability amplitudes $> 0.05$ mag. is the shallow Hipparcos sample to $V = 7.5$ (Rucinski 2004) (from now on called the “Hipparcos sample” or the “7.5 mag. sample”) consisting of 35 objects, with 1/3 in that number being new detections.

This sample suggests the relative spatial density of the EW binaries at a level of 0.2% of the FGK main sequence stars, but this fraction requires a confirmation by a larger sample, particularly for $M_V > +3.5$ where the Hipparcos sample contained very few objects.

2 AMPLITUDE DISTRIBUTION AND MISSING SYSTEMS

Spatial density estimates of variable stars are crucially dependent on the detection limitations: Photometric variability must be some 5 times larger than the photometric error, $\sigma$, for detection while another margin of $> 10 \sigma$ is needed for proper characterisation and assurance that the star is not one of rather common $\delta$ Sct or $\gamma$ Dor short-period pulsating main-sequence stars (Rucinski 2004). Theoretical predictions (Rucinski 2001) indicate that low-amplitude contact binaries should be very common as the amplitude distribution is expected to rise for amplitudes going to zero.

EW binaries discovered in the ASAS survey show a different amplitude distribution from that of the Hipparcos sample. Figure 1 gives the distribution for the Hipparcos sample (left panel) and for the ASAS sample (right panel), both compared with the theoretical amplitude distribution expected for random orbital inclinations and for a flat mass-ratio distribution, $Q(q) = \text{const}$ (Rucinski 2001). The latter assumption is made for lack of any evidence to the contrary and needs verification. Also, both observational samples in-
3 ABSOLUTE MAGNITUDE CALIBRATION

The previously proposed absolute magnitude calibration for contact binaries (Rucinski 1994; Rucinski & Duerbeck 1995; Rucinski 2004), is a linear one: 

\[ M_V = a_V \log P + a_{BV}(B - V)_0 + a_0, \]

where \((B - V)_0\) is the reddening corrected colour index (which can be replaced by say \((V - I)_0\)); it can predict \(M_V\) to about 0.2 – 0.25 mag. It has been used successfully for many applications, particularly for confirming or disproving membership of contact binaries in stellar clusters (Rucinski 1998, 2000). The main basis for the calibration is the Hipparcos sample (Rucinski 1994; Rucinski & Duerbeck 1997). This sample has been carefully scrutinized for multiplicity and for small, but measurable amounts of the local interstellar (IS) reddening. The former requirement is related to the high frequency of triple systems among contact binaries while the latter stems from the availability of sensitive indicators of small amounts of local reddening such as the linear polarization, EUV extinction or IS cirrus emission.

The calibrating sample is given in Table 1. It consists of 21 EW from the Hipparcos 7.5 mag. sample (Rucinski 2002). Except for for the orbital periods (known practically without any error) and for the parallax and parallax error data taken from the Hipparcos mission catalogue (not listed here, but available in previous tabulations), the remaining data have been modified: The known triple systems have here, but available in previous tabulations), the remaining

| Name       | \(V_{\max}\) | \(B - V\) | \(E_{B-V}\) | \(P(d)\) | \(M_V\) | \(\epsilon M_V\) |
|------------|--------------|-----------|------------|----------|---------|------------------|
| VW Cep     | 7.38         | 0.82      | 0.00       | 0.2783   | 5.17    | 0.06             |
| OU Ser     | 8.25         | 0.62      | 0.01       | 0.2968   | 4.41    | 0.13             |
| SX Crv     | 8.95         | 0.52      | 0.04       | 0.3166   | 4.01    | 0.24             |
| YY Eri     | 8.16         | 0.66      | 0.00       | 0.3215   | 4.43    | 0.14             |
| W UMa      | 7.76         | 0.62      | 0.00       | 0.3336   | 4.28    | 0.11             |
| GM Dra     | 8.65         | 0.48      | 0.03       | 0.3387   | 3.59    | 0.19             |
| V757 Cen   | 8.40         | 0.65      | 0.02       | 0.3432   | 4.10    | 0.17             |
| V781 Tau   | 8.55         | 0.58      | 0.02       | 0.3449   | 3.94    | 0.24             |
| GR Vir     | 7.81         | 0.56      | 0.01       | 0.3470   | 4.15    | 0.14             |
| AE Phe     | 7.56         | 0.64      | 0.00       | 0.3624   | 4.12    | 0.09             |
| YY Crt     | 8.64         | 0.62      | 0.01       | 0.3766   | 3.89    | 0.16             |
| V759 Cen   | 7.47         | 0.53      | 0.02       | 0.3940   | 3.41    | 0.13             |
| EX Leo     | 8.17         | 0.53      | 0.00       | 0.4086   | 3.13    | 0.24             |
| V566 Oph   | 7.47         | 0.41      | 0.03       | 0.4096   | 3.10    | 0.17             |
| AW UMa     | 6.84         | 0.33      | 0.01       | 0.4387   | 2.71    | 0.13             |
| CN Hyi     | 6.57         | 0.41      | 0.01       | 0.4561   | 2.72    | 0.08             |
| TY Men     | 8.11         | 0.29      | 0.01       | 0.4817   | 1.94    | 0.23             |
| RR Cen     | 7.32         | 0.34      | 0.03       | 0.6057   | 2.17    | 0.19             |
| IS CMa     | 6.87         | 0.31      | 0.01       | 0.6170   | 1.84    | 0.15             |
| V535 Ara   | 7.15         | 0.30      | 0.02       | 0.6293   | 1.83    | 0.22             |
| S Ant      | 6.29         | 0.30      | 0.01       | 0.6484   | 1.88    | 0.12             |

The period – luminosity calibration for the 21 EW systems with good Hipparcos parallaxes and free of triple-system complications. The open and closed circles mark systems bluer and redder than \((B - V)_0 = 0.5\), respectively. The line is given by: \(M_V = -1.5 - 12 \log P\) with the orbital period \(P\) in days. It was derived from 17 systems with \(\log P < -0.25\).

\[ V = 5 \log P - 25. \]

Figure 2. The period – luminosity calibration for the 21 EW systems with good Hipparcos parallaxes and free of triple-system complications. The open and closed circles mark systems bluer and redder than \((B - V)_0 = 0.5\), respectively. The line is given by: \(M_V = -1.5 - 12 \log P\) with the orbital period \(P\) in days. It was derived from 17 systems with \(\log P < -0.25\).
its value is frequently known much better. The table should be regarded as an improvement over the previous similar tabulations \cite{Rucinski95} in the treatment of the IS reddening and in the careful screening for triple components. The ASAS data presented by \cite{Paczynski06} are in the \( V \) band. The colour indices are currently unknown, but will be available in the future. We derive here a simplified \( M_V = M_V(\log P) \) calibration utilizing the known loose correlation of the periods and colour indices, as noticed long time ago by \cite{Eggen67}. We claim that a very simple relation of the form \( M_V = a_0 + a_P \log P \) may suffice in situations like the current one when an additional limit is added on the length of the orbital period. The very steep dependence is indeed visible in Figure 2. Some scatter is due to a range in the reddening corrected colour index, \( 0.28 < (B-V)_0 < 0.82 \); the spread is noticeable in the figure where different symbols are used for \((B-V)_0\) above and below 0.5. Four binaries with \( \log P > -0.25 \) are all blue, so a decision was made to use only 17 binaries with periods shorter than this limit. By using the bootstrap sampling technique of repeated least-squares solutions, we derived a simplified relation: \( M_V = -1.5(\pm 0.8) - 12.0(\pm 2.0) \log P \), with \( \sigma = 0.29 \) for a single object. The errors of the coefficients have been estimated from the bootstrap sampling distributions encompassing 67\% of the results.

If a simplified calibration works, a question arises whether the colour term is needed at all. The data have well established errors \( \pm \)\( M_V \) derived from the parallax errors, so one can check if \( \chi^2 = \sum (O - C)^2/\sigma^2 \) is approximately equal to the number of degrees of freedom. The 3-term linear fit \( M_V = a_0 + a_2 \log P + a_{BV} (B-V) \) gives \( \chi^2 = 13.4 \) for \( \nu = m - 3 = 14 \) degrees of freedom, thus indicating a basically perfect fit and the need of a 3-term fit. The simplified 2-term linear fit, \( M_V = -1.5 - 12.0 \log P \), gives \( \chi^2 = 52.9 \) for \( \nu = m - 2 = 15 \) degrees of freedom, confirming that indeed three terms are needed. However, we can invert the problem and ask if the decrease in \( \chi^2 \) due to the addition of the colour term is significant. It appears that the difference between \( \chi^2 \) and \( \chi^2 \) tested with the \( P \) Snedecor distribution \cite{Hamilton64} suggests a probability of an accidental improvement at the level of 37\%, quite a distance from the normally desired < 5\%, so it would appear that the third term is not needed after all. Thus, the situation is somewhat confused. However, a consideration of the involved physics strongly indicates that a colour term should be present in the calibration unless it is not available, as in the current application.

4 DISTANCES AND SPATIAL DENSITY

The limitation to periods \( \log P < -0.25 \) or \( P < 0.562 \) days means that from now on we will consider only the EW binaries from the main peak of period distribution, as shown in Figure 3. Thus, out of the full sample of 5384 EW binaries in the ASAS survey, from now on we will discuss the results for 3377 systems or 63\% of the whole sample or 73\% of the sub-sample of 4640 systems with \( P < 1 \) day. For a direct comparison of numbers with the Hipparcos sample, a correction factor of \( 1/0.73 \approx 1.37 \) must be applied. This factor, combined with the under-counting due to loss of low amplitude binaries (Section 2) implies that the ASAS counts must be multiplied by a factor of about 3\( \times \) carrying an uncertainty of about 30\%.

With the known values of \( M_V \), the distances are simply calculated from \( d = \text{dex}(V - M_V + 5)/5 \), where we neglect the interstellar reddening. As we can see in Figure 4 the distances are moderate, so this assumption is acceptable except for the bins of higher luminosities where the distances extend beyond a few hundred parsecs. Thus, we expect that for \( M_V < +3.5 \) our density estimates are too low. However, we are interested mostly in the luminosity function for fainter contact binaries where the Hipparcos sample \cite{Rucinski02} ran out of low luminosity objects.
Table 2. Table 2: The luminosity function for ASAS sample of EW systems with log \( P < -0.25 \). \( n \) is the number of EW systems in a 1-mag. wide bins centred at \( M_V \) within the distances \( r_1 \) and \( r_2 \). \( r_1 \) corresponds to \( V = 8 \) and \( M_V - 0.5 \) while \( r_2 \) corresponds to \( V = 13 \) and \( M_V + 0.5 \). \( \phi \) is the luminosity function in units of \( 10^{-7} \) stars/pc\(^4\); its error \( \phi \) is evaluated from \( \sqrt{n} \).

| \( M_V \) | \( n \) | \( r_1 \) (pc) | \( r_2 \) (pc) | \( \phi \) | \( \phi \) |
|---|---|---|---|---|---|
| 2.0 | 489 | 199.5 | 1258.9 | 0.80 | 0.04 |
| 3.0 | 729 | 125.9 | 794.3 | 4.74 | 0.18 |
| 4.0 | 564 | 79.4 | 501.2 | 14.61 | 0.62 |
| 5.0 | 229 | 50.1 | 316.2 | 23.62 | 1.56 |
| 6.0 | 26 | 31.6 | 199.5 | 10.67 | 2.09 |

Figure 5. The luminosity function for the EW systems with log \( P < -0.25 \) in the ASAS survey (the continuous line) is compared with the results based on the Hipparcos sample extending to \( V_{max} < 7.5 \) (the broken line) and with the solar neighbourhood data scaled down by factor 500\( \times \) (the dotted line). Note that for the direct comparison with the Hipparcos results, the ASAS counts have been multiplied by a factor of 3\( \times \). The error bars show the mean standard errors resulting from the statistical uncertainties only and do not include the systematic uncertainty of the ASAS detection correction factor estimated at about 30%.

The ASAS photometric survey covered the 5-magnitude interval \( 8 < V < 13 \). The two magnitude limits, expressed as distances, are shown as lines in Figure 4. The other limits come from our \( M_V \) calibration (Section 5) which is valid within \( 1.5 < M_V < 5.5 \). For each 1-mag.-wide bin in \( M_V \), we found the near and far limits (\( r_1 \) and \( r_2 \) in Table 2), and simply counted the systems in the respective volume \( 4\pi/3 \times C \times (r_2^3 - r_1^3) \) assuming that the survey South of \( \delta = +28^\circ \) covered \( C = 0.735 \) of the whole celestial sphere. The results are given in Table 2 while the luminosity function is shown in Figure 5.

5 THE LUMINOSITY FUNCTION

Figure 5 compares the ASAS luminosity function, after correction by 3\( \times \) (for systems missed because of the amplitude detection selection and of the removal of systems with \( P > 0.562 \) days), with the Hipparcos luminosity function and with the Main Sequence luminosity function (Widener et al. 1984) scaled down by a factor of 500 times. The ASAS and Hipparcos sample results are complementary, with the ASAS sample improving the luminosity function within the interval \( 3.5 < M_V < 5.5 \) where the Hipparcos sample had very few objects. While the luminosity function is better defined in the statistical sense with hundreds of binaries per \( \Delta M_V \) bin, the correction for the systematic effects by a factor of \( (3 \pm 1) \) leaves a rather wide margin for improvement.

The comparison of the luminosity functions in Figure 5 confirms the previously derived relative spatial frequency of contact binaries in the solar neighbourhood of 0.2\%. Although the relative frequency of bright contact binaries, \( M_V < +3.5 \), appears low at about 0.1\%, the lower numbers of intrinsically bright binaries may be caused by our neglect of the IS reddening and extinction and by the inapplicability of the simplified \( M_V \) calibration. The relative frequency reaches 0.2\% for the interval \( +3.5 < M_V < +5.5 \), but then drops to 0.1\% in the \( M_V = +6 \) bin, and to zero for still fainter objects. The sharp decline in the numbers of faint systems is related to the well established period cutoff at 0.215 – 0.22 days which still remains unexplained. It should be noted that the relative frequency may be higher in the central galactic disk at about 1/130 (Rucinski 1998) although this particular estimate suffered from photometric blending effects in the direction of the Galactic Bulge which may have raised the frequency by a factor of about 2\( \times \).

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3 The system CC Com delineated the cut-off at 0.2207 d. for a long time, but a new discovery in 47 Tuc by Weldrake et al. (2004) has moved it to a still shorter period of 0.2155 d. Short periods are expected and indeed observed in globular clusters (Rucinski 2000).