PREDICTED PROPERTIES OF ECLIPSING BINARIES OBSERVABLE BY GAIA

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ABSTRACT

Using a population synthesis model we estimate the fraction of stars of different types that are likely to show eclipses, as a function of the period. The population model is based on the *bse*-code from Hurley et al. (2002) which is a rapid binary evolution code that include all common effects in close binaries such as mass transfer, tidal locking, wind etc. We use this to evolve millions of systems from original distributions in separation, mass and eccentricity, with ages between zero and 12 Gyr, to get a population of systems representative of our Galaxy. The binary data from our model are then analysed in order to, statistically, see how many eclipsing systems we should have. This is done with a simple model where we neglect limb-darkening and other complicating effects. Assuming a random distribution of the inclination angle the probability of an eclipse of a given depth, Δm, can easily be calculated. Adding a reasonable fraction of true single stars, we can finally estimate the fraction of eclipsing binaries in limited areas of the HR-diagram, as a function of the period. A first comparison with observational data from the Hipparcos mission shows quite satisfying agreement, and extrapolation to Gaia should thus be a natural application. We find that Gaia will observe about 500 000 eclipsing binaries, this (surprisingly) small number arises from the fact that many eclipsing systems will not be detected by Gaia.

Key words: Binaries; Eclipses; Population synthesis.

1. INTRODUCTION

The study of eclipsing binaries is an important tool to get stellar parameters as well as general properties for binaries. The distribution of the depth of the eclipses are seldom studied, partly because the eclipsing systems discovered are done so in an unsystematic way and therefore are a most inhomogeneous sample. Some studies have been made before, Giuricin et al. (1983) investigate the implication of this to the mass ratio of binary systems, however, it is difficult to draw any definitive conclusions from such a sparse and inhomogeneous data sample.

The large scale surveys, such as Hipparcos, gives a much more complete sample and some idea of the true statistics, but unfortunately the number of eclipsing binaries are also here rather small (a couple of hundred). Gaia will increase this number drastically and we will have a complete sample of hundreds of thousand systems to study, which of course is a gold mine for statistical investigations. The question we are trying to answer in this article is how many eclipsing binaries will be observed by Gaia as well as how these will be distributed in periods and eclipse depth – given reasonable input values to simulate the Galaxy.

The eclipse probability depends mostly on the radius and the orbit size of the system. Since the evolution of binaries often include migration of the orbit size, it is important to start our simulation from a very wide period distribution in order to catch the systems where the orbit shrinks. Another very important factor is to include close binary interaction since it is the systems with short periods that have the largest probability for eclipses, this is done by using the *bse*-code by Hurley et al. (2002).

2. POPULATION SYNTHESIS MODEL

We are using a population synthesis model that evolves our population of stars from initial distributions of age, mass (m), mass ratio (q), distance (a), eccentricity (e) and metallicity (Fe/H). These quantities are chosen to match our Galaxy in a simple way. We have chosen the following set of simple, time-independent recipes as summarized below:

Ages: Constant star formation rate between 0-12 Gyr

System masses: IMF from Kroupa (2001)

$$\xi(m) \sim m^{a_i} \quad \begin{array}{ll} a_0 = 0.3 & 0.03 < m < 0.08 \\ a_1 = 1.8 & 0.08 < m < 0.50 \\ a_2 = 2.7 & 0.50 < m < 1.00 \\ a_3 = 2.3 & 1.00 < m < 50.0 \end{array}$$

Mass ratios: A small fraction (typically 20%) are kept as single stars, but the majority are split into doubles according to a fixed mass-ratio distribution:

$$f(q) = 0.446 \times [1 + 2N(0.2, 0.3) + \\ +2N(1.0, 0.05)],$$

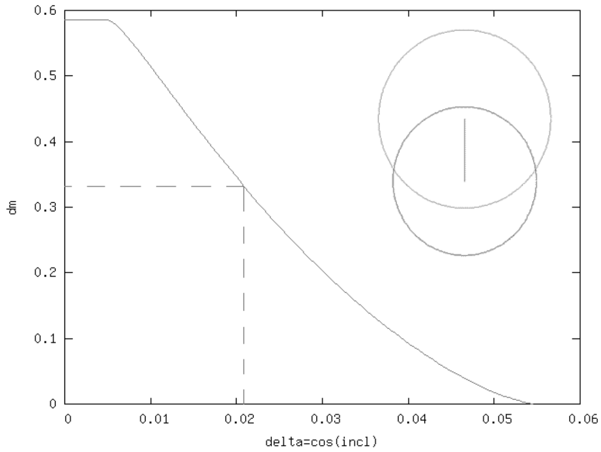

Figure 1. An illustration of how the eclipse depth, Δm, depends on the distance between the stars $d = \cos\ i$. The dashed curve gives the d corresponding to maximum eclipse Δm (see inlay).

where $N(m, s)$ stands for a normal distribution with a mean m and a standard deviation s, without the normalization denominator. This $f(q)$ is reasonably flat, somewhat similar to the Duquennoy & Mayor (1991) standard, but with a narrow excess of equal-mass pairs. It has however been lessened since used in Söderhjelm (2000).

Orbit sizes: The semi-major axes are taken from a log-normal Duquennoy & Mayor (1991) distribution; $f(\lg a) =$ N(1.5,1.5) $-3 < \lg a <5$ au

Eccentricities: Distributed thermally for the largest orbits turning smoothly into a uniform distribution at $a < 10$ au. The tidal evolution built into the *bse*-code produces usually a rapid circularization for periods below some 10 days.

Metallicities: A broad age-independent distribution similar to that observed in the solar neighbourhood Nordstöm et al. (2004).

Given these input values we use a rapid binary evolution code (*bse*) by Hurley et al. (2002) to evolve our systems as we would see them today. This is possible due to the fact that the *bse*-code can evolve millions of systems in a matter of hours. The code is very fast thanks to the fact that it approximates the evolutionary tracks in the HR-diagram with polynomials. It also includes all features associated with close systems such as:

mass transfer
tidal locking
circularisation
common-envelope
collision
supernova kicks
...

It is essential to have these close binary interactions for our study since eclipsing binaries are prefentialy seen when the stars are close to each other and therefore very likely to have undergone some kind of interaction. The *bse*-code is accurate only down to a bona fide stellar mass-limit around 0.08 $M_\odot$. For any component of lower mass, we have added an extra grid with data due to Baraffe et al. (1998), giving more realistic cooling brown dwarfs.

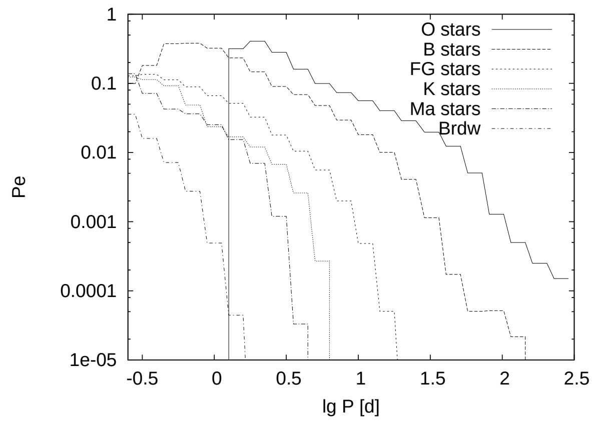

Figure 2. A histogram of the probability for an eclipse of at least a depth of 0.1 mag for a given period, for different types of systems. The brighter systems can be seen at much larger periods mainly because the size of the stars. O-systems cannot be closer than about 1.3 days due to this simple fact as well.

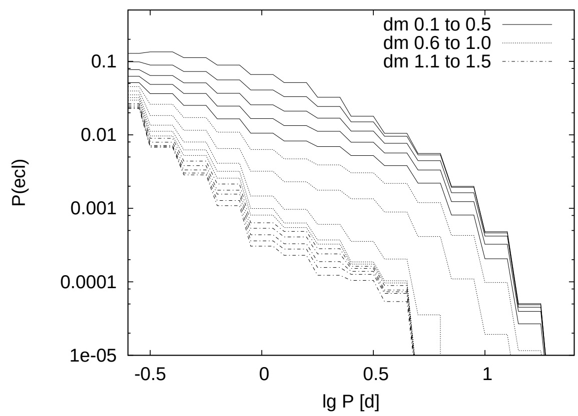

Figure 3. How the eclipse probability varies for F and G systems for different periods. The different lines give the probability for different eclipse depth, solid lines gives depth from 0.1 to 0.5 mag, the dashed lines is 0.6 to 1.0 while the dot-dashed lines is 1.1 to 1.5 mag.

The *bse* code gives 'theoretical' stellar parameters ($\lg T_{\rm eff}/M_{\rm bol}$), and our crude transformations to 'observed' ($V, V-I$) are based on Flower (1996) with some simplistic extensions towards cooler systems.

3. ECLIPSE MODEL

The population synthesis gives a number of binaries with known properties, among them the orbit size, period, stel-

Table 1. The probability to have an eclipse with a depth of at least 0.1 mag, for different periods (observe that only short period systems are in the table). Above is the mean probability for eclipses for the different bins, P_e, while the fraction of observed eclipsing binaries relative to all stars in the same HR diagram bin is below (O_e).

	P_e-values															
Bin	0.175	0.25	0.36	0.51	0.72	1.02	1.44	2.04	2.88	4.08	5.76	8.16	11.5	16.3	23.0	32.5
O	-	-	-	-	-	-	-0.50	-0.39	-0.55	-0.79	-1.00	-1.13	-1.25	-1.39	-1.54	-1.71
OB	-	-	-	-0.22	-0.31	-0.36	-0.44	-0.55	-0.74	-0.92	-1.04	-1.21	-1.41	-1.61	-1.89	-2.29
B	-0.87	-1.00	-0.74	-0.43	-0.42	-0.49	-0.63	-0.83	-1.05	-1.16	-1.32	-1.53	-1.74	-2.00	-2.39	-2.94
A	-0.92	-0.95	-0.79	-0.68	-0.69	-0.84	-1.04	-1.17	-1.26	-1.46	-1.69	-1.89	-2.16	-2.59	-3.18	-4.13
FG	-1.05	-0.89	-0.87	-0.95	-1.05	-1.18	-1.29	-1.49	-1.75	-1.98	-2.25	-2.70	-3.32	-4.30	-5.92	-
K	-0.93	-0.91	-0.95	-1.03	-1.31	-1.63	-1.77	-1.92	-2.17	-2.59	-3.57	-	-	-	-	-
M(a)	-0.70	-0.86	-1.15	-1.37	-1.44	-1.60	-1.81	-2.16	-2.92	-4.48	-	-	-	-	-	-
M(b)	-0.78	-1.16	-1.61	-1.73	-1.86	-2.16	-2.58	-3.64	-	-	-	-	-	-	-	-
Brdw	-1.00	-1.45	-1.80	-2.15	-2.56	-3.31	-4.35	-6.41	-	-	-	-	-	-	-	-
	O_e-values															
O	-	-	-	-	-	-	-4.19	-3.36	-3.12	-3.15	-3.20	-3.24	-3.30	-3.41	-3.51	-3.63
OB	-	-	-	-6.09	-4.30	-3.43	-3.05	-2.91	-3.01	-3.14	-3.22	-3.35	-3.50	-3.64	-3.86	-4.19
B	-6.73	-7.01	-6.11	-4.45	-3.47	-3.05	-2.92	-3.00	-3.14	-3.22	-3.35	-3.51	-3.68	-3.89	-4.25	-4.77
A	-5.97	-6.02	-4.83	-3.69	-3.20	-3.15	-3.26	-3.33	-3.42	-3.60	-3.81	-3.96	-4.20	-4.57	-5.13	-6.06
FG	-5.48	-4.93	-4.39	-4.02	-3.82	-3.72	-3.66	-3.72	-3.89	-4.14	-4.45	-4.90	-5.47	-6.41	-7.99	-
K	-5.34	-5.00	-4.67	-4.36	-4.29	-4.28	-4.19	-4.21	-4.48	-4.90	-5.86	-	-	-	-	-
M(a)	-4.09	-4.01	-4.08	-4.13	-4.08	-4.23	-4.39	-4.67	-5.38	-6.86	-	-	-	-	-	-
M(b)	-3.81	-3.96	-4.24	-4.33	-4.54	-4.85	-5.21	-6.23	-	-	-	-	-	-	-	-
Brdw	-4.22	-4.33	-4.50	-4.80	-5.30	-6.07	-7.04	-9.04	-	-	-	-	-	-	-	-

lar radii and luminosities. Assuming a random inclination angle, i, it is straightforward to calculate the likelihood to have an eclipse of a given depth. In our study, we take the simple approach and neglect limb darkening, as well as all light-curve complications due to tidal deformation and/or reflection effects. Once these assumptions are made the probability, $P_e(\Delta m)$, to have a primary eclipse with an eclipse depth larger than Δm is a simple matter of calculating eclipse light-curves at different inclinations. The radii relative to the orbit-size is $r_s = R_s/a$ and $r_g = R_g/a$, where s and g stand for smaller and greater, are the interesting parameters, together with the relative (V-band) luminosities L_s and L_g, where $L_s + L_g = 1$. In the uniform-disc approximation, it is easy to calculate the maximum eclipse depth (in magnitudes) as a function of the minimum distance between the components $d = (\cos i)$, see Figure 1. This function can now be (iteratively) inverted, to give the inclination corresponding to a given eclipse depth. Assuming random inclinations, the probability for an inclination above i is simply $\cos(i)$, and in this way we may calculate for each system the eclipse probabilities $P_e(\Delta m)$.

For main sequence stars of roughly constant size, the P_e-values typically decrease as a^{-1}, or as $P^{-2/3}$. Longer periods also mean narrower eclipses, however, and there is an observational bias against discovering such rare eclipses. To account for this effect, a non-zero P_e-value is only calculated if the Δm is larger than 0.1 magnitude for at least 5% of the orbit. We have then calculated the mean eclipse probabilities in small bins of period and in some 20 different areas of the HR-diagram. Because most eclipses involve a main-sequence star, the 10 bins along the MS are the most interesting ones. Generally, because the stellar radii increase with mass, the eclipse probabilities also increase with mass. For comparisons with observed eclipsing binaries, we have also calculated the fraction of eclipsing binaries (of a certain Δm) relative to all stars (binary and single) in the same HR diagram bin. These eclipsing binary fractions are called $O_e(\Delta m)$ and means over the HR diagram bins were derived as for $P_e(\Delta m)$.

4. RESULTS

From our model, we calculate how likely it is for a given system to eclipse to a depth of Δm at a period P. Using the means over HR diagram bins, we can construct histograms like Figure 2, giving the eclipse probability at a certain absolute magnitude and a certain period. The higher-mass stars are larger, and are more likely to eclipse even at long periods. There is also in each group a minimum period, corresponding to contact systems. In Figure 2, this limit is only visible for the large O-systems, otherwise it is hidden beyond the left edge of the diagram. Note also the logarithmic scale, the probability drops very fast as one moves to longer periods or less massive systems. In Figure 3 the probability for F and G stars ($2.5 < M_V < 5.5$) are plotted for increasingly deeper eclipses, Δm goes from 0.1 to 1.5 mag for the different curves. One can clearly see that the likelihood for deep eclipses is much less, a factor of about 100 for eclipses with $\Delta m \geq$ 1.0 in comparison to the shallow 0.1 eclipses.

We can summarize our P_e and O_e-means in tables giving the ($\log$) of the probability for an eclipse of (at least) a certain depth Δm as a function of period and absolute magnitude. In Table 1 is an example with $\Delta m >$ 0.1. The column headers give the mean periods in days.

5. PREDICTIONS FOR GAIA

As a test, we have applied the P_e results to a crude model galaxy designed to simulate the Gaia binary star observations. The model includes realistic close binaries, and using the above principles, we calculated an eclipse probability for each simulated binary, giving a direct estimate of the number of eclipsing binaries observable by Gaia. The same model Galaxy gives an HR-diagram that can be simply subdivided in the M_V 'bin'-system used for P_e, and it is a simple matter to derive the P_e summed over all

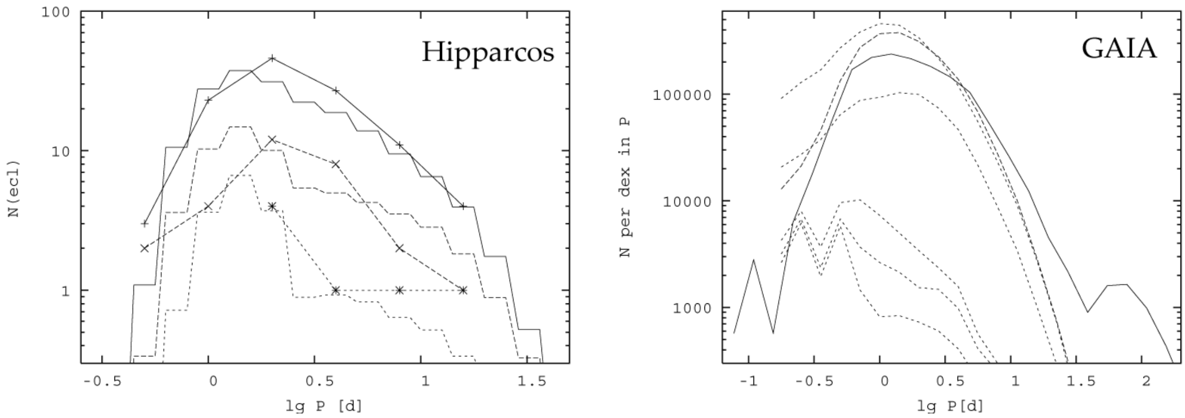

Figure 4. To the left is a comparison between the number of early type eclipsing binaries in the Hipparcos Catalogue (lines with points) and our theoretical B-star O_e data (lines). The three curves are for eclipses of minimum depth 0.1, 0.4 and 0.7 magnitudes. To the right are three different calculations of the number of eclipsing binaries (with $\Delta m > 0.1$) observable by Gaia. The solid curve is a direct calculation, using individual P_e for each binary system and including giant systems. The long dashed curve is an estimate derived from mean eclipse probabilities P_e (main sequence only). The upper short dashed curve is a result using O_e means, and the differences relative to the long dashed curve comes from a different input period-distribution. The lower short dashed curves correspond to eclipse depths larger than 0.5, 1.0, 1.5 or 2.0 magnitudes.

absolute magnitudes. As seen in the right of Figure 4, the two calculations do agree as well as could be expected. The long-period deviation is easily explained as the (rare) eclipses in giant-star systems, which were by design not included in P_e means. At the peak (and in the total numbers), the P_e-results are too high by about a factor of two. The effect is largest at faint apparent magnitude, and it is probably caused by extinction effects changing the M_V distributions in the broad P_e bins.

By oversight, the input distribution of semi-major axes in the galaxy model was truncated at a larger value than in the population synthesis. Therefore, the even simpler calculation, using only $O_e(M_V)$ plus the number of stars in each of the M_V-bins gives more close eclipsing binaries than the P_e calculation, but with a virtually identical long-period part. Apart from this well-understood effect, however, the O_e-means can be used to give a qualitatively correct picture of the period- and Δm-distributions for the eclipsing binaries observable by Gaia. Because of the low eclipse-probabilities, the ‘true’ curve in Figure 4 can only be defined when both the magnitude range and the sky coverage are large. The P_e/O_e-method can be applied to an arbitrarily small area of sky or magnitude range, however, giving expectation values instead of unusable ‘small-number’ counts. This is important especially for the deep eclipses, which are seen in Figure 4 to be relatively very scarce.

A crude but satisfying test of our procedures could be obtained from Hipparcos data. Assuming reasonably complete discovery of eclipsing binaries, we could make the ‘small-number’ statistical comparison in Figure 4. In this case our O_e data needed only to be multiplied by the number of stars in the Hipparcos sample (22 600) to give the expected number of eclipsing binaries in successive factor 2 period bins.

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REFERENCES

Baraffe, I., Chabrier, G., Allard, F., Hauschildt, P.H., 1998, A&A, 337,403

Duquennoy, A., Mayor, M., 1991, A&A, 248,485

Giuricin, G.,Mardirossian, F.,Mezzetti, M., 1983, A&A, 121,42-44

Hurley, J.R., Tout, C.A., Pols, O.R., 2002, MNRAS, 329:897-928

Flower, P.J., 1996, ApJ,469,355

Kroupa, P., 2001, MNRAS, 322,231

Nordström, B., Mayor, M., Andersen, J., et al., 2004, A&A, 418,989

Söderhjelm, S., 2000, AN 321,165