Magnetic braking in Solar-type close binaries

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Abstract. In tidally locked binaries the angular momentum loss by magnetic braking affects the orbital period. While this effect is too small to be detected in individual systems, its signature can be seen in shape of the orbital period distribution of suitable samples. As a consequence, information on the braking mechanisms can be obtained – at least in principle – from the analysis of the distributions, the main problems being the selection of a large and homogeneous sample of binaries and the appropriate treatment of the observational biases.
New large databases of variable stars are becoming available as by-products of microlensing projects, which have the advantage of joining, for the first time, sample richness and homogeneity. We report the main results of the analysis of the eclipsing binaries in OGLE-I catalog, that contains several thousands variables detected in a pencil-beam search volume towards the Baade's Window. By means of an automatic filtering algorithm we extracted a sample of 74 detached, equal-mass, main-sequence binary stars with short orbital periods (i.e., in the range $0.19 < P < 8$ days) and derived from the presently observed period distribution, after correction for selection effects, the expected slope of the braking law.
The results suggest an AML braking law very close to the "saturated" one, with a very weak dependence on the period. However we are still far from constraining the precise value of the slope, because of the important role played by the observational bias.

1. Introduction

The evidence that stellar rotation depends on spectral type was given by Struve and Elvey (1931), but the idea of evolution with time came much later: Kraft (1967) found a relation between age and rotational velocity for late-type stars in open clusters, and Skumanich (1972) quantified it in a time decay with a dependence of the form: $v_{rot} \propto t^{1/2}$. That is equivalent to a variation of the angular velocity $\dot{\omega} \propto \omega^3$, and applies to the slow rotation regime ($10 - 20$ km/s).

The first physical interpretation of these facts – and of the slow rotation of the Sun as well – was the magnetic braking model by Schatzman (1959), who pointed out that a relevant angular momentum loss can be produced even with negligible mass loss, if the star has a magnetic field forcing the corotation of the outgoing stellar wind. Then the lever arm of the braking torque is comparable to the Alven radius that in late-type stars, which have convective envelopes and host a dynamo, can be much larger than the stellar radius.

Schatzman's model set the general framework of rotational evolution in late-type stars, whose details turned out to be much more complex than initially thought. Stauffer & Hartmann (1987) and Soderblom et al. (1993) surveyed rotation among the late type stars of clusters of different ages, down to a treshold of ~ 10 km/s and showed the existence of very fast rotators (up to 200 km/s) in young clusters (as α Per and the Pleiades). The evolution of the $v \sin i$ distribution, and in particular the rapid convergence in rotation rates for small masses at the Hyades age, cannot be explained by the Skumanich relation, and possibly a model with a different (saturated) braking law is necessary.

Tidally locked binaries, with at least one late-type dwarf component, can be an independent important source of information on the braking mechanism. Their most useful property – in this respect – is that thanks to the efficient synchronization mechanisms, the angular momentum taken away from the outgoing wind is actually subtracted from the orbital reservoir and affects the orbital period, which is an easily measurable quantity. The final result of angular momentium loss (AML) is shrinkage of the orbit, period decrease and spin-up of the components. The evolution of the orbital period contains therefore, information on the braking mechanism and indirectly on the star internal structure.

While the AM losing late-type stars that are single or form wide binaries experience a decay of rotation, those in tidally locked binaries spin faster and faster, while approaching to each other, and eventually form a contact binary.

The typical time-scale of AM evolution in these binaries (of the order of the Gyr, depending on model details) is too long to expect a measurable effect in the period of individual systems (Maceroni, 1999), as the timespan of observations for the best studied binary is still around a hundred years. However, the signature of AML can be in principle seen in the evolution of the orbital period distribution of binary samples.

An initial period distribution will evolve into the presently observed one according to the details of the model for AM loss and transfer. The main difficulty to face in handling this problem is sample selection. Previous woks were based either on the all-sky late type Main Sequence binary sample (Maceroni and Van 't Veer 1991=MV91, Maceroni, 1992), or on the Hyades one (Stepien 1995 = ST95). The former is a rich but unavoidably inhomogeneous sample, the latter is homogeneous and coeval, but very small. When, recently, large and homogeneous catalogs of binaries were published as by-products of microlensing searches, new possibilities were open for these studies.

We present in this paper the results obtained from the first of these catalogs that has been made public and accessible on-line, that from the OGLE-I experiment (Udalski et al. 1994). This provides a sample of $\sim$ 1200 eclipsing and in great majority close binaries, in the Baade's window direction.

We will first shortly describe the theoretical model of AML evolution and the algorithm used for the automatic extraction of the binary sample of interest, and then compare our results relative to the period distribution evolution with those of previous works. The general properties of the OGLE-I sample of pre-contact eclipsing binaries are presented in Maceroni and Rucinski (1999, MR99).

2. The evolution of the orbital period distribution

The evolution of the angular momentum of a tidally locked binary is determined by:

- the braking law, which is usually expressed as $\dot{\omega} \propto \omega^{\alpha}$. This corresponds to a variation of the rotational AM, $H_{rot} \propto P_r^{-\alpha}$.
- the AM transfer between spin and orbit because of tidal locking. Studies on tidal coupling in a close binary with late-type dwarf component (P_{orb} of a few days) show that the phenomenon has a time-scale much shorter than the others of relevance here, so that the coupling can in practice be considered istantaneous. Hence, $\dot{H}_{orb} \equiv \dot{H}_{rot}$, and thanks to spin- orbit synchronization $P_{orb} \cong P_{rot} = P$, dropping the suffixes.
- the internal rotational profile of the star. This is often assumed to be uniform (i.e. rigid body rotation).

As by definition $\dot{H}_{orb} \propto P^{-2/3}\dot{P}$, the rate of period change is $\dot{P} \propto P^{2/3-\alpha}$ which can also be written, introducing the time scale of period evolution, as:

$$\left|\frac{\mathrm{d}\log P}{\mathrm{dt}}\right| = \tau \propto P^{\alpha+1/3}. \tag{1}$$

The way a period distribution will look because of evolution depends on the period evolution function (PEF), on the distribution at formation time and its time dependence. The simplest case is that of a sample of binaries all formed at the same time t_0. If their initial period distribution (IPD) is $f_0(\log P)$ the evolved one at a later time t_* (e.g. the present time of observation), $f_*(\log P)$, results from the requirement of constancy of the total number of the systems:

$$f_*(\log P) = f_0(\log P)\left|\frac{\mathrm{d}\log P(t_0)}{\mathrm{d}\log P(t_*)}\right| = f_0(\log P)\frac{\tau_*}{\tau_0} \tag{2}$$

which contains the period evolution from the time t_0 to t_* as: $P_* = P_*(P_0)$ (for brevity, we use P_n to signify $P(t_n)$).

Thus, the present period distribution function $f_*(\log P)$ is proportional to the ratio of the present and the initial time-scales (i.e. rapid evolution will locally deplete the distribution). Obviously, in the more realistic case of time-independent formation process

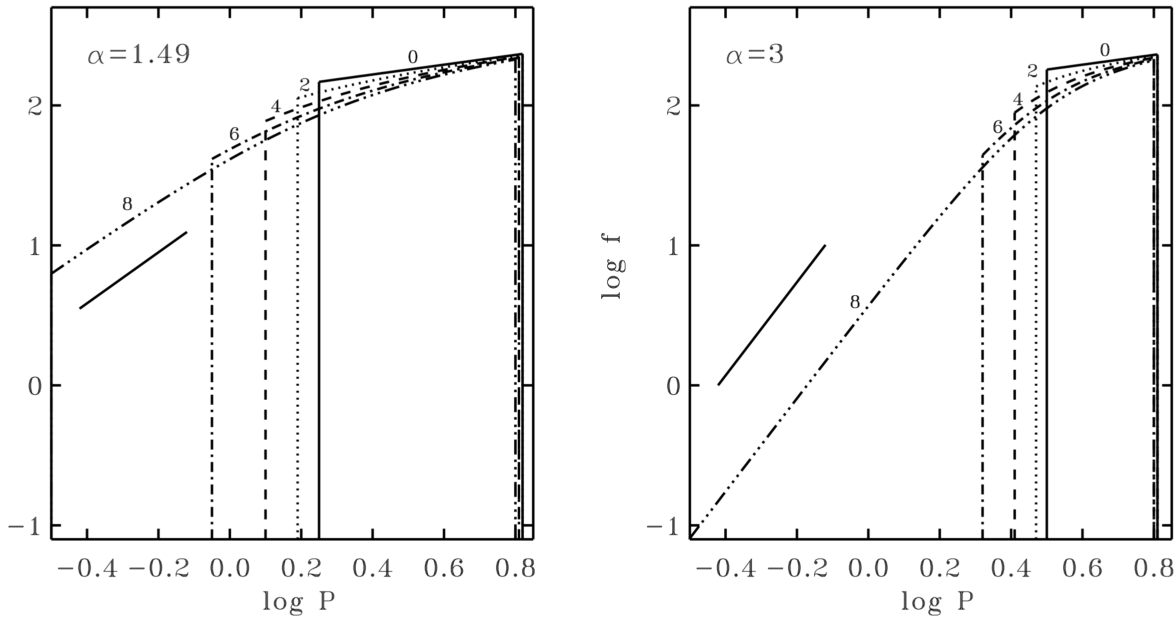

Figure 1: The figure shows the expected evolution of the period distribution for two values of α, 1.49 and 3, following the theoretical predictions of Stępień (1995) and Skumanich (1972). The starting distribution in both cases have the same, gently-positive slope $\beta = 0.35$, as in $f_0 \propto P^{\beta}$. The initial period ranges are different for each panel; they have been adjusted to populate the distribution down to 0.3 days after the time interval of 8 Gyrs. The numbers by the lines give the ages of the repective populations in Gyr. The short vectors in the left parts of the panels give the asymptotic slopes $\alpha + 1/3$, as expected from considerations in the text.

over some time interval, the present period distribution would be a result of an integration of the right side of Eq. 2 over the whole time interval.

The stars in Baade's Window are not coeval but in their majority probably belong to a relatively old population, possibly older than ~ 5 Gyr (Ng et al. 1996, Kiraga et al. 1997), so that products of recent formation events are quite unlikely to be seen there. In this case, the existing PEF models (as those of MV91 or ST95) predict that the systems presently observed as pre-contact binaries come from a initial period range where the time-scale of period change was very long and weakly time dependent for the first few Gyr of evolution. As a consequence the result of the integration over the formation time will be proportional to $f_0 \tau_* / \tau_0$, where τ_0 will actually be a mean over the formation time. Thus, as long as we study only the shape of the period distribution, we can just use the expression in Equation 2.

The analytical form of the initial period distribution is somewhat uncertain for binaries of short period. A possible and reasonable choice is the extrapolation of the period distribution of Duquennoy and Mayor (1991). That has the shape, in the logarithm of the period, of a wide Gaussian with a maximum at $\log P = 4.8$ and $\sigma \log P = 2.3$ (with the period P expressed in days); it can be approximated, within the range $0 < \log P < 1$ days, by $N(\log P) \propto P^{\beta}$ with $\beta = 0.35$.

The present period distribution obtained from the initial distribution and Eqs. 1, 2, will then be:

$$f_*(\log P) \propto P^\beta \left[1 + (\alpha + 1/3)\,\frac{T}{\tau_*}\right]^{\frac{\beta-\alpha-1/3}{\alpha+1/3}} \tag{3}$$

This turns out to be simply proportional to the IPD for $t \ll \tau$ and to the timescale τ_* for $t \gg \tau$.

Figure 1 shows, as example, two evolving distributions, which have been computed using the α value of Skumanich relation ($\alpha = 3$) and the lower one, $\alpha = 1.49$, corresponding to a local fit of the braking law as derived in ST95. In both cases one can notice that the slope of short period part of the initial distribution quickly converges to the $\alpha + 1/3$ value. We can therefore expect to derive, by comparison of IPD with the present distribution of the Baade's window sample, the α value. To this purpose we should first find a criterion to extract the sample of pre-contact MS binaries and a way to correct the observed distribution for the selection effects.

3. The sample of equal mass pre-contact MS binaries

The OGLE-I catalog of eclipsing binaries provides for each system the period, the $B - V$ color at maximum, and the I light curve.

The extraction of the sample of pre-contact MS binaries was performed by means of a filtering procedure based on the first coefficients of the Fourier decomposition of the light-curve, similar to that formulated by Rucinski (1997, R97). As shown in that paper, the pair of coefficient a_2 and a_4 from the light curve decomposition

$$l(\phi) = \sum_i a_i \cos(2i\pi\phi) \tag{4}$$

form a powerful separator of contact and non-contact systems. That because the various coefficients contain different information on the light curve shape. In particular a_1 reflects the difference between the two eclipses and for equally-deep minima goes to zero; the second, a_2 is the largest of the coefficients and represents the total amplitude of the light variations; a_4 expresses the light curve "peakedness" and goes to small values for the light curves of contact systems. Figure 2 shows an example of the various Fourier components for the pre-contact system BW3 V38 (Maceroni and Rucinski 1997).

The details of the filtering procedure are fully described in MR99, we recall here its steps:

- non-contact/ contact binary separation by means of the locus $a_4 = a_4(a_2)$ (see Fig. 5 of R97).
- selection of systems whose light curves display similar depth minima. This was necessary because of the limited information contained in the single color light curves. The only way to reject, without color information, the unwanted evolved Algol-type

systems was the selection on the basis of unequal minima. That, unfortunately but unavoidably, rejects as well unevolved systems with components of unequal temperature (that is equivalent on the MS to unequal masses). This selection was performed by means of the a_1 and a_2 coefficients, taking into account a necessary scaling of the accepted difference in depth with the light curve amplitude, and comparing the sample distributions of a_1 and a_1/a_2 with those of in a typical similar eclipse depth sample (W UMa system) and our sample. The result were boudary conditions on $|a_1|$ and $|a_1/a_2|$, namely $|a_1| \leq 0.017$ and $|a_1/a_2| \leq 0.2$ (see Fig 4 of MR99).

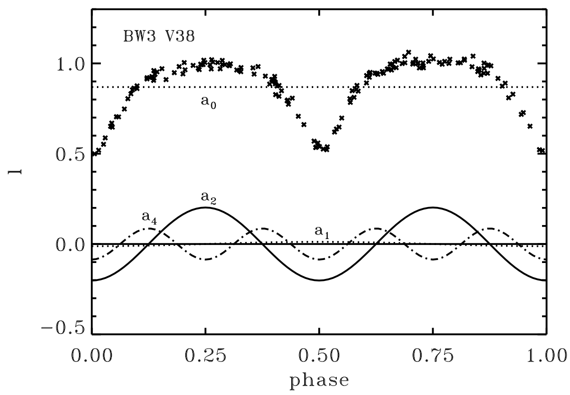

Figure 2: The light curve of the OGLE system BW3 V38 and some of its first Fourier components. Each cosine curve is labeled with the corresponding coefficient as defined in the text. The constant term a_0 is also shown. It is evident that a_2 gives the main contribution to the light curve amplitude, a_1 to the difference between minima (in this case very small), and that a_4 expresses the eclipse "peakedness", giving the main contribution to minimum wing shape.

As the resulting sample still retained a few systems with long period and evolved (presumably giant) components, we set an upper limit to the period of dwarf tydally locked systems to 8^d.

The final sample contained 77 systems. For all of these the distance, d, the unreddened colors and absolute magnitudes were derived by an iterative process, in an approach somewhat similar to that described in R97, and identical to that used in the study of the system BW3 V38 (MR97). An adopted absolute-magnitude calibration $M_I = M_I((V-I)-E_{V-I}(d))$ for the main sequence (Reid and Majewski 1993), shifted by 0.75 magnitude to allow for two identical stars, was used for a first guess of d and reddening E_{V-I}. An iterative procedure was then started with the reddening allowed to vary linearly with distance between zero and the maximum value derived from the background Bulge giants by Stanek (1996), and assuming that E^{max}_{V-I} is reached at the distance of 2 kpc, and then does not increase.

After determination of the unreddened colors, three too blue systems were rejected. The sample of pre-contact late-type systems from OGLE-I sample eventually contains 74 systems. While its size is still moderate, it has to be noticed that it less than a factor of two smaller than the previously known sample of all-sky binaries studied by Maceroni and Van't Veer (1991) and much larger than the Hyades one (12 systems).

The main advantage of the automatic filtering still is, in this case, the objectivity of the selection, as a manual selection could still be considered feasible, though long, for the OGLE-I catalog. However, the same procedures used in this study can be applied, as they are, to the larger samples from other surveys, when those will be available to the scietific community.

4. The period distribution of OGLE-I pre-contacts

The complete study of the properties of the OGLE-I sample can be found in MR99. Here we briefly present those relevant to the definition of the period distribution and describe a simple way to correct it for observational selection effects.

From the $V - I$ color we inferred the spectral types and tried to check if the period distribution, and the AML loss features, showed any dependence on it. Our main concern was that fully convective M-type systems, could show a different distribution related to peculiar AML mechanisms, but statistical test on the (small) sample of 10 presumably M-type stars and the remaining 64 F-G-K systems (MR99), in which the sample could be splitted, gave no indication of such a dependence. Moreover, no correlation was found between the periods and colors or absolute magnitudes. One does not expect, therefore, dependence of the distribution on the distance, that makes easier the treatment of the data in a magnitude limited sample as OGLE is.

The final observed period distribution of the whole sample, in bi-logarithmic form, is shown in Fig. 3. Contrary to the models of Fig. 1, the slope of the distribution is negative. A weighted linear least square fit to the histogram of Fig. 3, as $\log N = A_0 + A_1 \log P$ (with weigths given by poissonian errors in bins $\Delta \log P + 0.2$), gives for the whole sample $A_0 = 1.05 \pm 0.06$, $A_1 = -0.79 \pm 0.16$, or $A_0 = 1.02 \pm 0.07$, $A_1 = -0.80 \pm 0.17$ for the FGK sub-group. The values of χ^2 for the fits were 3.1 and 3.7 for the 6 log-period bins. The linear fits are thus only marginally appropriate, but definitely much better than flat distributions.

To better define the uncertainty limits on the coefficients A_0 and A_1, a Monte-Carlo experiment has as well been conducted in which weighted fits were made to several thousand artificial Poisson distributions with the same *mean* values for each log-period bin (because the mean values do not form a linear dependence, such fits provide more realistic estimates of the uncertainties of the coefficients A_0 and A_1). The results, expressed in terms of the distributions of the individual determinations of the coefficients around their median values, are given in Table 1.

We think that the reason of the negative slope is to be found in selection against discovery scaling in proportion to the orbital period. The chances of eclipse detection rapidly decrease with increasing separation of the components because:

- the range of inclination yielding eclipses shrinks
- the eclipses become pregressively shorter
- in a time limited survey as OGLE is, fewer orbital cycles are observed

A simple way of estimating probability of discovery of a system is the evaluation of solid angle subtended by the sum of the fractional radii $(r_1 + r_2)/a$, relative to hemisphere visible by a distant observer, i.e. by dividing it by 2π steradian. This takes into account the first two effects of period lengthening mentioned above. This relative solid angle is given by the integral of the eclipse relative durations over the range of inclinations that can

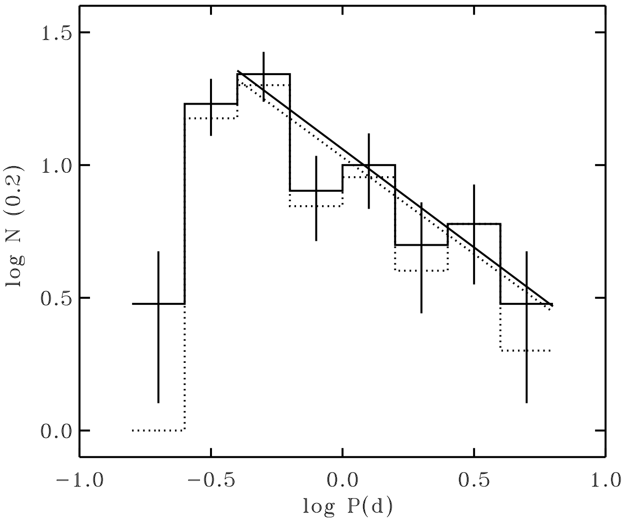

Figure 3: The orbital period statistics in logarithmic units of the number of systems in bins $\Delta \log P = 0.2$. The histogram is shown for the full sample of 74 systems (solid lines) and the FGK group of 64 systems (dotted line), but – for clarity – the Poisson errors are shown as vertical bars for the full sample data only. The sloping lines show the linear fits, as described in the text.

result in eclipses, which evaluates to $1 - \left(\sqrt{1 - \left(\frac{r_1 + r_2}{a}\right)^2}\right) \approx \left(\frac{r_1 + r_2}{a}\right)^2$. For fixed radii, the probability of discovery of an eclipsing system scales as the inverse of its orbital separation in square, $\propto a^{-2}$. A discovery-probability scaling according to a^{-2} should be a particularly reasonable assumption for the equal-mass, hence presumably equal-radius component systems that we selected. The correction factor that we should use to multiply the statistics of periods is then expected to behave as: $corr \propto a^2 \propto M_{tot}^{2/3} P^{4/3}$. The mass dependence can be further removed by observing that, as we described above, the orbital periods in our sample do not correlate with the color or absolute magnitude. We can therefore assume that they do not correlate with the total mass of the system, M_{tot}. The correction factor to apply to the histograms in Figure 3 would be then: $corr \propto P^{4/3}$. Thus the correction to the slope in the bi-logarithmic distribution, C, turns out to be $C = 4/3$.

The relation between the braking-efficiency exponent, α, the observed slope, A_1, and the observational selection correction, C is: $\alpha = A_1 + C - 1/3$. As any results will in fact be dominated by the systematic effects characterized by C, we set $A_1 = -0.75 \pm 0.20$, that is an intermediate value between the directly derived value and that from the Montecarlo experiment of Table 1 (the error estimate comes from the Monte Carlo experiment). The corresponding value for the braking exponent is:

$$\alpha = 0.25 \pm 0.20 \tag{5}$$

Therefore, the material from the OGLE-I survey favours a quite flat (saturated) braking law, this result in good agreement with the known saturation of the activity indicators at short periods first pointed out by Vilhu (1982).

Actually subsequent work (see for instance Wichmann et al. 1998) shows that the activity indicators, which can be related to the AML rate, show a change of slope – from a saturated to a steeper law – at rotation periods around 3–4 day. The small size of our sample and the consequent relatively coarse binning did not allow us to properly analyze this feature: the expected change of the slope would fall in the tail of our distribution

Term	median	1-sigma range	2-sigma range
Ful l			
A_0	1.07	$-0.07, +0.05$	$-0.14, +0.11$
A_1	-0.74	$-0.18, +0.21$	$-0.40, +0.38$
FGK			
A_0	1.03	$-0.08, +0.06$	$-0.15, +0.11$
A_1	-0.73	$-0.22, +0.22$	$-0.43, +0.49$

Table 1: Results of the Monte-Carlo determinations of the coefficients A_0 and A_1.

since we currently have only three systems in the bin $P > 5$ days. On a qualitative ground, Figure 3 does suggest that an exclusion of the last bin from the fit would result in a slightly flatter braking law, but we feel that an estimate of the slope based on such reduced data would actually be an over-interpretation of the available material.

5. Discussion and conclusions

Our results strongly depends on the power of the correction applied to the distribution because of observational biases, however there are some plausibility arguments in favour of values of C not too different from that we derived.

For instance, a genuine negative slope of the distribution could be obtained if there were no selection effects ($C = 0$) and that would be in agreement with the distribution of short-period systems in Hyades as found by Griffin (1985). However, it is hard to assume the OGLE survey free from observational biases.

The result by Stepien (1995), with its local linear fit for $\log P \leq 1^d$ giving $\alpha = 1.49$, would instead imply a C almost twice our value, $C = 2.57$. A stronger selection cannot be excluded, but we consider it unluckily.

On the basis of the available data we can draw at least one firm conclusion on the general shape of the distribution. There is no evidence in our homogeneous sample for any bimodal period distribution, similar to that found by Farinella et al. (1979) with a dip at $\log P \simeq 0.2$. We believe that this dip and a secondary maximum in the distribution were most probably produced by misclassification of evolved systems as consisting of main-sequence components. Our smooth period distribution, without any structure, implies quite a different form of the braking law with respect to that derived by MV91 and Maceroni (1992). Though the functional form remains partly similar, in the sense of a "saturated" braking at short orbital periods ($\alpha = 0$), the other main feature, namely the sudden increase of the braking efficiency for rotation of $\sim 10\omega_\odot$ is no longer mandated by the data. That feature was the necessary to reproduce the bimodality of field G-type system distribution which showed a pronounced dip around $\log P = 0.2$ days (Farinella et al., 1979).

The highly desiderable improvements for future are in two different directions: first that of richer sample, which would allow more detailed studies on the spectral type dependence of the distribution and hence of the AML properties. But a meaningful improvement could as well be achieved if multi-band similar catalogs were available, since the single color curves implied a too selective filtering, which excluded potentially interesting system from our study.

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